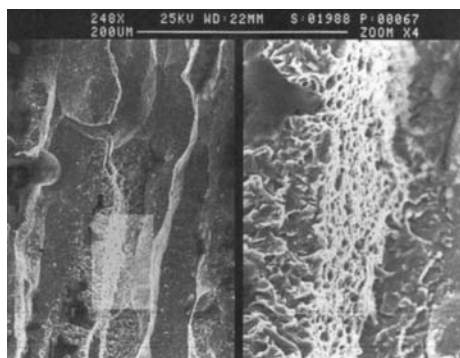
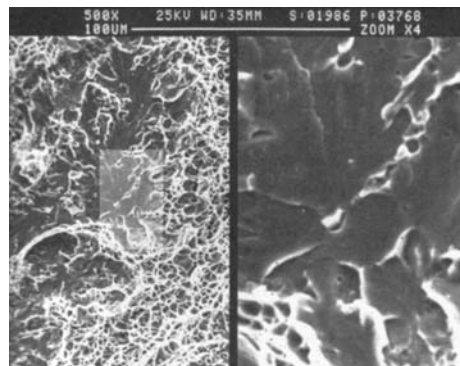


Guide to Weldability



Carbon and Low Alloy Steels

GUIDE TO WELDABILITY:

CARBON and LOW ALLOY STEELS

**How to get the needed results
and stay out of trouble**

Written by
Fritz Saenger, Jr., P.E., IWE

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INTRODUCTION

You are responsible for the operation of an independent fabrication shop, a similar facility within a manufacturing organization, or a maintenance facility in a factory of any type. "Things" are brought to you to fabricate or repair. This guide is intended to help you ask the right questions, and from the answers, select the method, materials, and procedures that will produce the result desired from your "customer," or direct you to more comprehensive guidance that may be needed to produce the desired results.

ACKNOWLEDGMENTS

Most of the information in this reference guide is condensed from information in the current edition of *The Welding Handbook* and *Welding Metallurgy*, Linnert Volume 1, both published by The American Welding Society. Additional sources include AWS D1.1/D1.1M:2004, *Structural Welding Code—Steel*, Jefferson's *Welding Encyclopedia*, 18th Edition, The Lincoln Electric Company *Procedure Handbook of Arc Welding*, and the *ASM Handbook*, Volume VI.

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BASIC SAFETY PRECAUTIONS

Burn Protection. Molten metal, sparks, slag, and hot work surfaces are produced by welding, cutting, and allied processes. These can cause burns if precautionary measures are not used. Workers should wear protective clothing made of fire-resistant material. Pant cuffs, open pockets, or other places on clothing that can catch and retain molten metal or sparks should not be worn. High-top shoes or leather leggings and fire-resistant gloves should be worn. Pant legs should be worn over the outside of high-top shoes. Helmets or hand shields that provide protection for the face, neck, and ears, and a head covering to protect the head should be used. In addition, appropriate eye protection should be used.

Electrical Hazards. Electric shock can kill. However, it can be avoided. Live electrical parts should not be touched. The manufacturer's instructions and recommended safe practices should be read and understood. Faulty installation, improper grounding, and incorrect operation and maintenance of electrical equipment are all sources of danger.

All electrical equipment and the workpiece should be grounded. The workpiece lead is not a ground lead. It is used only to complete the welding circuit. A separate connection is required to ground the workpiece. The workpiece should not be mistaken for a ground connection.

Fumes and Gases. Many welding, cutting, and allied processes produce fumes and gases which may be harmful to health. Avoid breathing the air in the fume plume directly above the arc. Do not weld in a confined area without a ventilation system. Use point-of-welding fume removal when welding galvanized steel, zinc, lead, cadmium, chromium, manganese, brass, or bronze. Do not weld on piping or containers that have held hazardous materials unless the containers have been inerted properly.

Compressed Gas Cylinders. Keep caps on cylinders when not in use. Make sure that gas cylinders are chained to a wall or other structural support. Do not weld on cylinders.

Radiation. Arc welding may produce ultraviolet, infrared, or light radiation. Always wear protective clothing and eye protection to protect the skin and eyes from radiation. Shield others from light radiation from your welding operation.

The use of filtering masks or airline respirators will be required if it is determined that personnel are being exposed to excessive pollutants.

Additional information on welding safety may be obtained from the American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126. ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, and the AWS *Safety and Health Fact Sheets* are available online and free of charge on the AWS website: <http://www.aws.org/technical/facts/>.

CHAPTER 1

The Questions (you need to ask)

What is the product and how will it be used?

In other words, what does the product do? Is the weld a simple connection that bears a light static (non-fluctuating) load, or are the welds subject to highly fluctuating loads so that a small defect could grow into a crack and cause a catastrophic failure? Will it be subjected to low temperatures, e.g., winters in the north where temperatures well below 0°F can be encountered? (Some steels become brittle at such temperatures.)

What is the material?

Find out what specification is used to purchase the steel. Some of the more common types of steel are discussed in Chapter 2. If there is no specification, ask if the material is “plain carbon steel” or “mild steel,” or (at the other extreme) “tool steel.” In most cases, the former materials are relatively easy to weld and somewhat “forgiving.” The latter materials require extreme care if they are to be welded satisfactorily.

There are some simple tests to help determine the general class of material that you have, but there is no substitute for the actual composition or the purchasing specification.

What specifications or codes apply to the welding rods or electrodes (wires), and to the finished product, if any?

Most general fabrication is covered by agreement between the customer and the fabricator, with applicable specifications on drawings and related notes. However, you need to know if the work is covered by a code or specification that has legal standing and/or requires approval of a third party, which may require qualification of procedures, operators, materials, or other factors. Examples are the AWS D1.1/D1.1M:2004, *Structural Welding Code*—

Steel, the American Society of Mechanical Engineers (ASME) *Pressure Vessel Code*, various U.S. Military Standards, and others. If you see reference to such codes and standards on drawings, notes, or specifications, you and your customer need to reach an agreement on how these requirements will be handled. Certification, qualification, or conformance to such “third party” requirements is covered in detail by each code, and is outside the scope of this guide.

Are there welding procedure requirements? Make sure you understand what is required!

Your customer may require the use of:

- a specific welding process,
- a specific welding material (type and perhaps even the brand or manufacturer),
- a specific range of welding conditions,
- “qualified” welding operators (qualified by whom and to what standard?),
- a written welding procedure subject to the customer’s approval.

NOTE: Even if your customer does not require a formal procedure, you should consider preparing one. Then, test your operators to ensure that they can produce satisfactory welds using the procedure. A sample form for preparing an internal record or “control document” is included in Part 8 of this guide. Such a record has many benefits, especially if the job is to be repeated. The control document can be particularly useful if there are problems with the finished product on inspection or in service.

What are the postweld requirements?

Postweld requirements are as follows:

- Specific inspection and/or testing of the finished product,
- A specific post-weld heat treatment, e.g., stress relief,
- Painting, plating, or other surface treatment.

NOTES

[illegible]

CHAPTER 2

Key Background Information

What is Steel?

Steel is by far the world's most widely used structural material, largely because it is relatively inexpensive to produce. Steel also can be modified to perform in a wide variety of applications by the addition of small amounts of other materials, called *alloying*, and by a wide range of heat treatments and mechanical treatments, e.g., *hot and cold rolling*.

The steels covered by this guide contain more than 90% iron (Fe), iron that is usually produced by smelting iron ore in blast furnaces or the melting of steel scrap. The iron produced has a high level of carbon (C), typically as much as 3%, and if poured into a mold it will solidify into *cast iron*. Cast iron is still widely used for machine bases, engine blocks, and other applications where its ability both to absorb vibration and to provide dimensional stability are valuable characteristics. However, because of its structure, cast iron cannot be rolled into thin sections, is difficult to weld, and is unable to handle bending stresses—all of which limit its use. Converting this iron into steel by processes that reduce the carbon content well below 1% and allow the introduction of small amounts of other elements, results in a wide range of materials that are the basis for most of the steel products we use today.

Why is Steel a Unique Structural Material?

Steel is uniquely valuable because of *phase transformation*—a fundamental characteristic of iron that is found in only a few other metals (most of which are not suitable for general use). All metals in solid state have a distinct *crystal structure*, i.e., the arrangement of the atoms of the metal and any other elements that may be present. Iron is different because its crystal structure changes as it is heated and cooled. These changes in crystal structure, along with the resulting changes in mechanical properties (e.g., strength, ductility, and toughness), can be greatly affected by small changes in chemical composition and rates of heating and cooling.

For example, even the simplest carbon steel, with carbon content below 0.2% and less than 1% (total) of manganese and silicon (the most common alloying elements) will become hard and brittle if

quenched rapidly when still “red” hot. If cooled more slowly, the structure at room temperature will likely be relatively soft and ductile.

Terms You May Hear

Austenite—the high temperature solid phase (in carbon and low-alloy steels).

FCC (face-centered cubic).

Ferrite, BCC (body-centered cubic), in several forms:

- **Acicular**—desirable structure in low alloy weld metal.
- **Grain Boundary**—undesirable structure.
- **Polygonal**—undesirable structure, formed on slow cooling.

Martensite—a hard, brittle phase, body-centered tetragonal (BCT) formed on rapid cooling (or at slow cooling rates in certain high alloy materials).

Pearlite—a layered structure of ferrite and cementite, an iron-carbon compound, found in medium to high carbon steels.

Bainite (lower)—generally desirable structure found in alloy steel weld metal.

As illustrated in Figure 2.1, simple carbon steel solidifies into BCC “delta” ferrite then transforms to FCC austenite, then to BCC “alpha” ferrite, when cooled slowly. If cooled very rapidly, or *quenched*, the structure called *martensite* may be formed. When a phase transformation takes place there is a change in density, which causes high internal stresses and sometimes results in cracking. Also, particularly with the rapid cooling rate of welds and range of composition due to the incomplete mixing of the filler metal with the base metal, the room temperature weld may be a mixture of ferrite(s), pearlite, bainite, martensite, and other structures.

Solidification typically starts at many points in a liquid, called *nucleation sites*. From these points the individual atoms arrange themselves in a geometric structure, growing as a single *grain* until they encounter other grains growing toward them from other directions. Figure 2.2 is a *simplistic representation* of grain growth from a single nucleation site. Where grains meet they form a *grain boundary*. Here

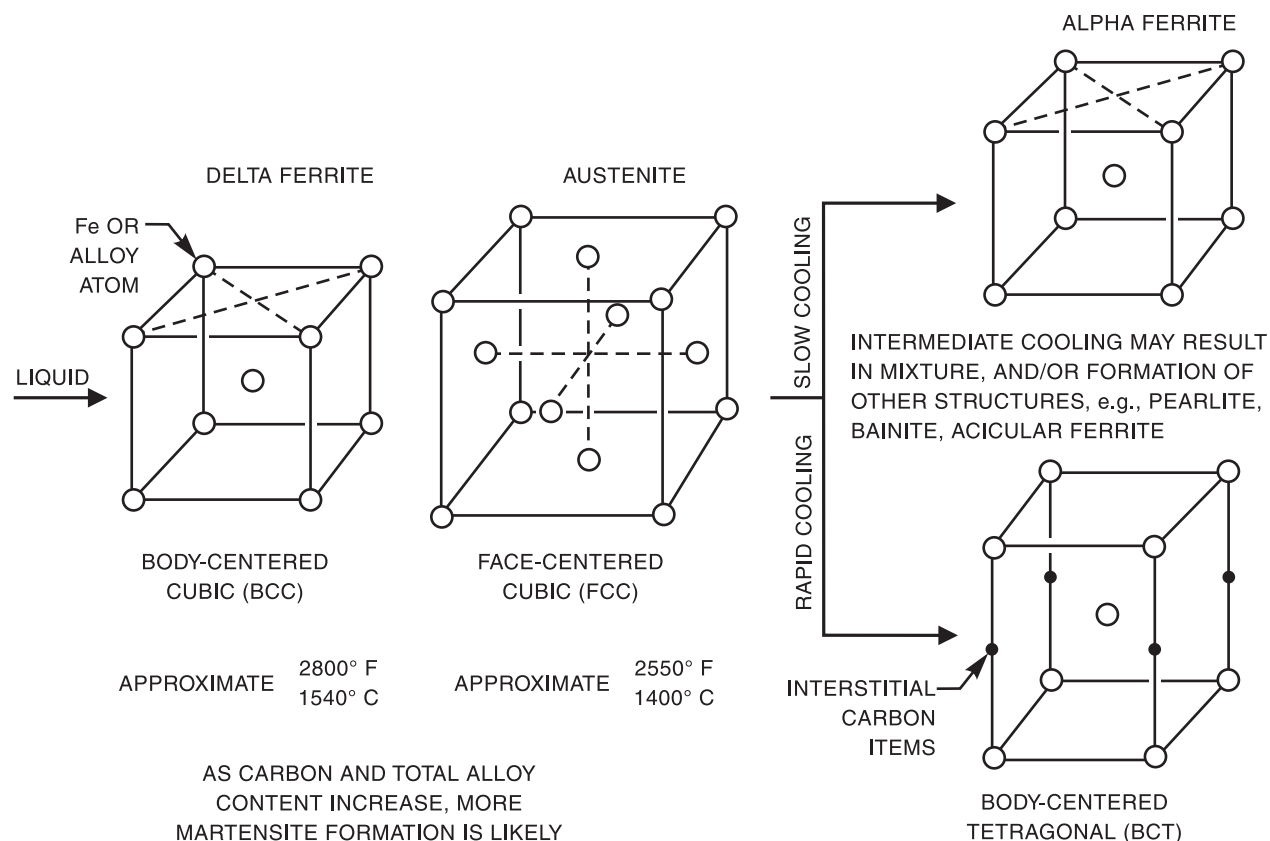


Figure 2.1—Structural changes in low carbon steel weld metal on cooling from liquid.

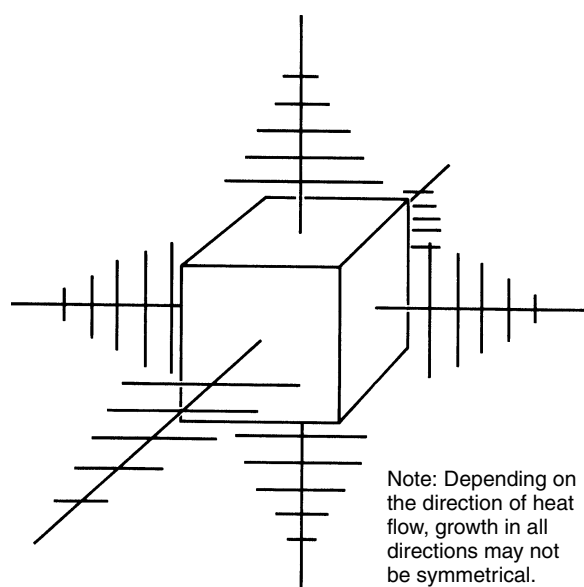


Figure 2.2—Pattern of dendritic growth from a crystal during solidification.

the orientation of atoms will not be orderly and there may be concentrations of some elements that didn't fit into the expanding grains. Figure 2.3 illustrates boundaries between grains with different orientations, and Figure 2.4 is a cross section of a weld where these boundaries are clearly visible. Because of the rapid cooling associated with most welding, the solidification grain size may persist to room temperature. However, in a multi-pass weld, the heating associated with successive passes will often cause the grains to "recrystallize," as they pass through phase changes, resulting in a finer grain structure that is usually associated with improved mechanical properties, particularly ductility and toughness. (This phenomenon may not occur with alloys that do not exhibit phase changes on heating/cooling, such as the austenitic stainless steels. In this case, repeated heating may cause undesirable grain growth.)

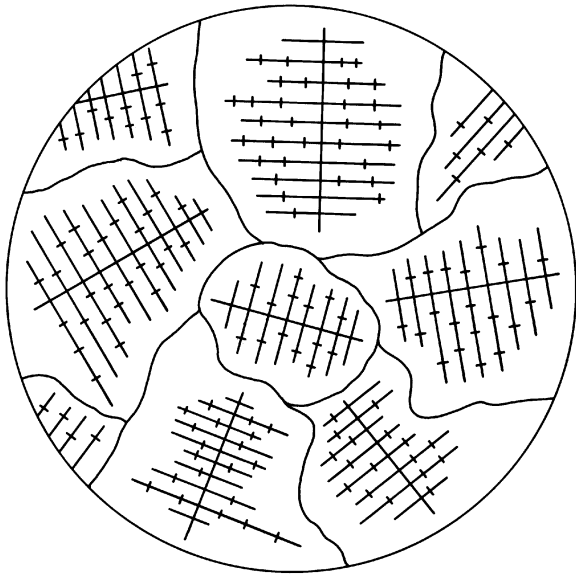
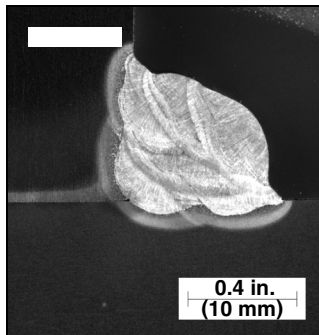


Figure 2.3—Grain size and shape in solidified metal are determined by the manner in which the branches of dendrites meet.



Photograph courtesy of Edison Welding Institute (EWI)

Figure 2.4—Weld cross section showing grain structure from initial solidification and “recrystallization” caused by heat of successive weld passes.

Alloying elements such as manganese (Mn), Silicon (Si), Molybdenum (Mo), Chromium (Cr), Nickel (Ni), Vanadium (V), Copper (Cu) and sometimes others are added to control these transformations and achieve the desired combination of mechanical properties. These elements can replace iron in the basic matrix (*substitutional alloying*), while a few are small enough to fit in between the iron atoms (*interstitial alloying*). These structures are illustrated in Figure 2.5. Both types of alloying place stresses on

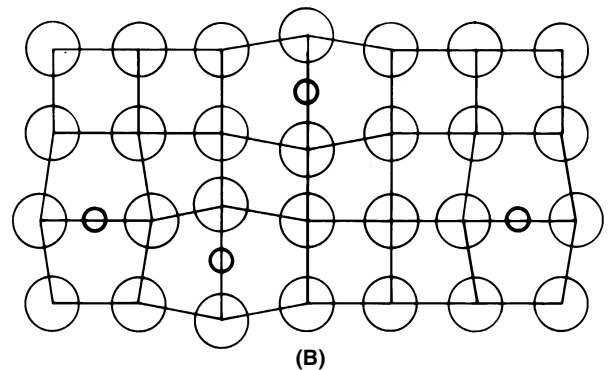
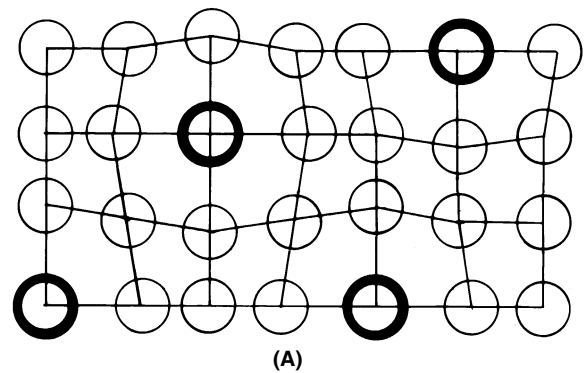


Figure 2.5—Schematic illustration of (A) Substitutional and (B) Interstitial solid solutions.

the matrix and strengthen it, but interstitial elements have a very powerful effect and can initiate cracking. From the point of view of welding, hydrogen is perhaps the most dangerous element in this respect, but others, such as arsenic, must also be kept very low by the steel maker, or the base metal will be sensitive to cracking.

Both substitutional and interstitial alloying have limits, and above these limits the alloy elements may form chemical compounds with iron or other elements. For example, sulfur forms a low-melting compound with iron that will remain liquid long after the alloy has solidified, and shrinkage stresses may result in cracks. Sulfur compounds in base metal can also wind up being rolled to films that can result in lamellar tearing. (Lamellar tearing is described in Table 5.1.)

Note: A reminder to the reader is that a weld “sees” a much different pattern of heating and cooling than may have been experienced by the base material. That is the

fundamental reason that welding filler metals may have substantially different compositions than the base materials. More on that in Chapter 4.

Common Steels You May Encounter

Tables 2.1–2.5 list many of the steels in common use, but there are others. See Chapter 9 for a list of the groups that publish steel specifications.

What if no information or identification is available?

If no one can tell you what you have, there are some simple tests that can help avoid serious difficulty. These are shown on Figure 2.6. This guide covers only the carbon steel group; if any of the tests shown in Figure 2.6 indicate you have another type of material, e.g., stainless steel, manganese steel, high sulfur steel, etc., the recommendations of this guide may not apply.

Note: if you are given material identified as “wrought iron,” but it is going to be used for decorative or security purposes, it is probably just low or medium carbon steel, as true wrought iron is only produced in limited quantities for special applications.

Properties of Steel—What the “Numbers” Mean

Table 2.6 lists some of the properties that may accompany specifications for steel and/or welds. It is important that you understand these characteristics. In many cases, it is just as important to know how the test was conducted in order to interpret these numbers properly.

Figure 2.7 illustrates typical tensile test specimens. Note that the “rectangular” specimen shows the weld in the center, an example of a “transverse tensile test”; the round specimen could have the same orientation, but it is often oriented longitudinally (in the direction of welding) and used to measure weld metal properties separately from the base material. *The published properties of filler metals are measured in this manner.*

Figure 2.9 is a typical “stress/strain” curve from a tensile test, illustrating the basis for the measurements described above.

Some Additional Important Terms

Elastic Behavior—most structures are designed to function in a range where the materials are not loaded to the point at which permanent deformation takes place. Perhaps the best example of this is a spring. If you pull (or push) on a spring up to a certain point, it will return to its original shape when released. If you pull further, it will take a “set” and will not return to its original shape. Some points in the spring have been loaded beyond their “elastic limit” and *plastic deformation* has occurred.

Plastic Behavior—materials loaded beyond their elastic limit either permanently deform, or they break. Some materials, such as glass, exhibit essentially no plastic behavior, while soft metals such as copper can be extensively deformed before they fail. Most steels can be formed by stamping, forging, swaging, or rolling to achieve their final shape, a common example of plastic behavior.

Transition Temperature—the temperature or range of declining temperatures over which the impact energy absorbed in a Charpy V-Notch (CVN) test drops sharply, and the fracture appearance changes from rough and torn (*shear fracture*) to crystalline or faceted (*brittle fracture*). In general, though individual codes have specific requirements and limitations, it is considered risky to place structures in service at temperatures below the transition temperature exhibited in the CVN test, or in other fracture toughness tests.

Work Hardening—virtually all metals become harder and stronger when they are permanently deformed (by rolling, drawing, swaging, forging, etc.) They also lose ductility and will eventually fail if cold working is continued beyond a certain point. Ductility of a work-hardened steel can often be largely restored by annealing, but the more complex alloys may require special heat-treating to obtain original properties.

Residual Stress—stress present in parts of a structure due to mechanical working, or due to shrinkage resulting from the uneven heating and cooling effects of welding. (See Chapter 3.)

Table 2.1—Composition and Strength Requirements of Typical ASTM Carbon Steels

Application	ASTM Standard	Type or Grade	Typical Composition Limits, % ^a			Tensile Strength		Minimum Yield Strength	
			C	Mn	Si	ksi	MPa	ksi	MPa
Structural Steels									
Welded buildings, bridges, and general structural purposes	A 36	—	0.29	0.80–1.20	0.15–0.40	58–80	440–552	36	248
Welded buildings and general purposes	A 529	—	0.27	1.20	—	60–85	414–586	42	290
General purpose sheet and strip	A 570	30, 33, 36, 40, 45, 50	0.25 0.25	0.90 1.35	— —	49–55 60–65	338–379 414–448	30 45	207 310
General purpose plate (improved toughness)	A 573	58 65 70	0.23 0.26 0.28	0.60–0.90 0.85–1.20 0.85–1.20	0.10–0.35 0.15–0.40 0.15–0.40	58–71 65–77 70–90	440–489 448–531 483–621	32 35 42	221 241 290
Pressure Vessel Steels									
Plate, low and intermediate tensile strength	A 285	A B C	0.17 0.22 0.28	0.90 0.90 0.90	— — —	45–65 50–70 55–75	310–448 345–483 379–517	24 27 30	165 186 207
Plate, manganese-silicon	A 299	—	0.30	0.90–1.40	0.15–0.40	75–95	517–655	40	276
Plate, low-temperature applications	A 442	55 60	0.24 0.27	0.60–0.90 0.60–0.90	0.15–0.40 0.15–0.40	55–75 60–80	379–517 414–552	30 32	207 221
Plate, intermediate and high-temperature service	A 515	55 60 65 70	0.28 0.31 0.33 0.35	0.90 0.90 0.90 1.20	0.15–0.40 0.15–0.40 0.15–0.40 0.15–0.40	55–75 60–80 65–85 70–90	379–517 414–552 448–586 483–621	30 32 35 38	207 221 241 262
Plate, moderate and low-temperature service	A 516	55 60 65 70	0.26 0.27 0.29 0.31	0.60–1.20 0.85–1.20 0.85–1.20 0.85–1.20	0.15–0.40 0.15–0.40 0.15–0.40 0.15–0.40	55–75 60–80 65–85 70–90	379–517 414–552 448–586 483–621	30 32 35 38	207 221 241 262
Plate, carbon-manganese-silicon heat-treated	A 537	1 ^b 2 ^c	0.24 0.24	0.70–1.60 0.70–1.60	0.15–0.50 0.15–0.50	65–90 75–100	448–621 517–689	45 55	310 379
Piping and Tubing									
Welded and seamless pipe, black and galvanized	A 53	A B	0.25 0.30	0.95–1.20 0.95–1.20	— —	48 min. 60 min.	331 414	30 35	207 241
Seamless pipe for high-temperature service	A 106	A B C	0.25 0.30 0.35	0.27–0.93 0.29–1.06 0.29–1.06	0.10 min. 0.10 min. 0.10 min.	48 min. 60 min. 70 min.	331 414 483	30 35 40	207 241 276
Structural tubing	A 501	—	0.26	—	—	58 min.	400	36	248
Cast Steels									
General use	A 27	60–30	0.30	0.60	0.80	60 min.	414	30	207
Valves and fittings for high-temperature service	A 216	WCA WCB WCC	0.25 0.30 0.25	0.70 1.00 1.20	0.60 0.60 0.60	60–85 70–95 70–95	207–586 483–655 483–655	30 36 40	207 248 276
Valves and fittings for low-temperature service	A 352	LCA ^{c,d} LCB ^{c,d} LCC ^{c,d}	0.25 0.30 0.25	0.70 1.00 1.20	0.60 0.60 0.60	60–85 65–90 70–95	414–586 448–621 483–655	30 35 40	207 241 276
a. Single values are maximum unless otherwise noted. b. Normalized condition. c. Quenched and tempered condition. d. Normalized and tempered condition.									

Table 2.2 Typical AISI–SAE Compositions

AISI-SAE No.	Composition wt.% (single values are maximums)				
	C	Mn	Si*	P	S
Carbon Steels					
1006	0.08	0.45	0.25	0.04	0.05
1010	0.08–0.13	0.30–0.60	0.35	0.04	0.05
1020	0.17–0.23	0.60–0.90	0.35	0.04	0.05
1030	0.27–0.34	0.60–0.90	0.35	0.04	0.05
1040	0.36–0.44	0.60–0.90	0.35	0.04	0.05
1050	0.47–0.55	0.60–0.90	0.35	0.04	0.05
1060	0.55–0.66	0.60–0.90	0.35	0.04	0.05
1070	0.65–0.73	0.60–0.90	0.35	0.04	0.05
1080	0.74–0.88	0.60–0.90	0.35	0.04	0.05
1095	0.90–1.04	0.30–0.50	0.35	0.04	0.05
Manganese-Carbon					
1513	0.10-0.16	1.10-1.40	0.35	0.04	0.05
1527	0.20-0.29	1.20-1.50	0.35	0.04	0.05
1541	0.36-0.44	1.35-1.65	0.35	0.04	0.05
1566	0.60-0.71	0.60-0.71	0.35	0.04	0.05
*Silicon levels may vary widely by manufacturer, and can be significantly lower than the maximum shown here.					

Stress Relieving—uniform heating of a structure to a temperature sufficient to relieve all or most of the residual stresses resulting from welding, followed by uniform cooling. This works because all steels “lose” strength as temperatures increase, so local yielding, sometimes called *relaxation* takes place. Stress relieving typically reduces welding-induced distortion, and makes the structure more stable.

Annealing—heating to eliminate the effect of cold working, or of rapid or uneven cooling that has created an undesirable (micro)structure. Full annealing takes the material above the full transformation to austenite, followed by slow cooling to create a uniform “soft” structure. “Process” annealing raises the temperature to a point below any transformation to austenite, lowering the hardness and removing most residual stresses.

Normalizing—as with annealing, the material is heated uniformly to a temperature above the full transformation to austenite, but it is usually following by rapid cooling, i.e., quenching in water or oil, and subsequent tempering to achieve the desired combination of strength and toughness.

Tempering—heating to temperatures below the transformation point to restore ductility to a quenched structure.

Note: If terms such as Dynamic Tear, Drop Weight, Explosion Bulge, and Fracture Toughness are used in relation to the structure, do not make welds without the close guidance of a technical professional, e.g. welding engineer, metallurgist, designer; one who is familiar with the service that the structure will see, and the relevant specification that will almost certainly apply.

Table 2.3—ASTM Specifications for High-Strength Low-Alloy Structural Steels

ASTM Specification	Type or Grade	Composition, % ^a										Minimum Tensile Strength		Minimum Yield Strength	
		C	Mn	P	S	Si	Cr	Ni	Mo	V	Other	ksi	MPa	ksi	MPa
A 242	1	0.15	1.00	0.15	0.05		—	—	—	—	0.20 min Cu	63–70	434–482	42–50	289–344
A 441	—	0.22	0.85–1.25	0.04	0.05	0.30	—	—	—	—	0.20 min Cu, 0.02 min V	60–70	413–482	40–50	275–344
A 572	42 ^b	0.21	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	60	413	42	289
	50 ^b	0.23	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	65	448	50	344
	60 ^b	0.26	1.35	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	75	517	60	413
	65 ^b	0.26	1.65	0.04	0.05	0.30	—	—	—	—	0.20 min Cu	80	551	65	448
A 588	A	0.10–0.19	0.90–1.25	0.04	0.05	0.15–0.30	0.40–0.65	—	—	0.02–0.10	0.25–0.40 Cu	63–70	434–482	42–50	289–344
	B	0.20	0.75–1.25	0.04	0.05	0.15–0.30	0.40–0.70	0.25–0.50	—	0.01–0.10	0.20–0.40 Cu	—	—	—	—
	C	0.15	0.80–1.35	0.04	0.05	0.15–0.30	0.30–0.50	0.25–0.50	—	0.01–0.10	0.20–0.50 Cu	—	—	—	—
	D	0.10–0.20	0.75–1.25	0.04	0.05	0.50–0.90	0.50–0.90	—	—	—	0.30 Cu, 0.05–0.15 Zr; 0.04Nb	—	—	—	—
	E	0.15	1.20	0.04	0.05	0.15–0.30	—	0.75–1.25	0.10–0.25	0.05	0.50–0.80 Cu	—	—	—	—
	F	0.10–0.20	0.50–1.00	0.04	0.05	0.30	0.30	0.40–1.10	0.10–0.20	0.01–0.10	0.30–1.00 Cu	—	—	—	—
	G	0.20	1.20	0.04	0.05	0.25–0.70	0.50–1.00	0.80	0.10	—	0.30–0.50 Cu; 0.07 Ti	—	—	—	—
	H	0.20	1.25	0.035	0.040	0.25–0.75	0.10–0.25	0.30–0.60	0.15	0.02–0.10	0.20–0.35 Cu; 0.005–0.030 Ti	—	—	—	—
	J	0.20	0.60–1.00	0.04	0.05	0.30–0.50	—	0.50–0.70	—	—	0.30 min Cu; 0.03–0.05 Ti	—	—	—	—
A 633	A	0.18	1.00–1.35	0.04	0.05	0.15–0.50	—	—	—	—	0.05 Nb	63–83	434–572	42	289
	C	0.20	1.15–1.50	0.04	0.05	0.15–0.50	—	—	—	—	0.01–0.05 Nb	65–90	448–620	46–50	317–344
	D	0.20	0.70–1.60	0.04	0.05	0.15–0.50	0.25	0.25	0.08	—	0.35 Cu	65–90	448–620	46–50	317–344
	E	0.22	1.15–1.50	0.04	0.05	0.15–0.50	—	—	—	0.04–0.11	0.01–0.03 N	75–100	517–689	55–60	379–413
A 710	A	0.07	0.40–0.70	0.025	0.025	0.35	0.60–0.90	0.70–1.00	0.15–0.25	—	1.00–1.30 Cu; 0.02 min Nb	65–90	448–620	55–85	379–586
	B	0.06	0.40–0.65	0.025	0.025	0.20–0.35	—	1.20–1.50	—	—	1.00–1.30 Cu; 0.02 min Nb	88–90	606–620	75–85	517–586

a. Single values are maximum unless otherwise noted.
b. These grades may contain niobium, vanadium, or nitrogen.

Table 2.4—ASTM Specifications for High-Strength Low-Alloy Steels for Pressure-Vessel Plate

ASTM Specification	Type or Grade	Composition, %*										Minimum Tensile Strength		Minimum Yield Strength	
		C	Mn	P	S	Si	Cr	Ni	Mo	V	Other	ksi	MPa	ksi	MPa
A 202	A	0.17	1.05–1.40	0.035	0.040	0.60–0.90	0.35–0.60	—	—	—	—	75–95	517–655	45	310
	B	0.25	1.05–1.40	0.035	0.040	0.60–0.90	0.35–0.60	—	—	—	—	85–110	586–758	47	324
A 203	A	0.23	0.80	0.035	0.040	0.15–0.30	—	2.10–2.50	—	—	—	65–85	448–586	37	255
	B	0.25	0.80	0.035	0.040	0.15–0.30	—	2.10–2.50	—	—	—	70–90	482–620	40	275
	D	0.20	0.80	0.035	0.040	0.15–0.30	—	3.25–3.75	—	—	—	65–85	448–586	37	255
	E	0.23	0.80	0.035	0.040	0.15–0.30	—	3.25–3.75	—	—	—	70–90	482–620	40	275
A 204	A	0.25	0.90	0.035	0.040	0.15–0.30	—	—	0.45–0.60	—	—	65–85	448–586	37	255
	B	0.27	0.90	0.035	0.040	0.15–0.30	—	—	0.45–0.60	—	—	70–90	482–620	40	275
	C	0.28	0.90	0.035	0.040	0.15–0.30	—	—	0.45–0.60	—	—	75–95	517–655	43	296
A 225	C	0.25	1.60	0.035	0.040	0.15–0.40	—	0.40–0.70	—	0.13–0.18	—	105–135	723–930	70	482
	D	0.20	1.70	0.035	0.040	0.10–0.50	—	0.40–0.70	—	0.10–0.18	—	75–105	517–723	55–60	379–413
A 302	A	0.25	0.95–1.30	0.035	0.040	0.15–0.30	—	—	0.45–0.60	—	—	75–95	517–655	45	310
	B	0.25	1.15–1.50	0.035	0.040	0.15–0.30	—	—	0.45–0.60	—	—	80–100	551–689	50	344
	C	0.25	1.15–1.50	0.035	0.040	0.15–0.30	—	0.40–0.70	0.45–0.60	—	—	80–100	551–689	50	344
	D	0.25	1.15–1.50	0.035	0.040	0.15–0.30	—	0.70–1.00	0.45–0.60	—	—	80–100	551–689	50	344
A 353	—	0.13	0.90	0.035	0.040	0.15–0.30	—	8.50–9.50	—	—	—	100–120	689–827	75	517
A 735	—	0.06	1.20–2.20	0.04	0.025	0.40	—	—	0.23–0.47	—	0.20–0.35 Cu; 0.03–0.09 Nb	80–115	551–792	65–80	448–551
A 736	—	0.07	0.40–0.70	0.025	0.025	0.35	0.60–0.90	0.70–1.00	0.15–0.25	—	1.00–1.30 Cu; 0.02 min Nb	72–105	496–723	55–75	379–517
A 737	B	0.20	1.15–1.50	0.035	0.030	0.15–0.50	—	—	—	—	0.05 Nb	70–90	482–620	50	344
	C	0.22	1.15–1.50	0.035	0.030	0.15–0.50	—	—	—	0.04–0.11	0.03 Nb	80–100	551–689	60	413
*Single values are maximum unless otherwise noted.															

Table 2.5—Composition of Selected Heat-Treatable Low-Alloy (HTLA) Steel

AISI-SAE or Other Designation	Composition, wt.%						
	C	Mn	Si	Cr	Ni	Mo	V
1330	0.28–0.33	1.60–1.90	0.15–0.30	—	—	—	—
1340	0.38–0.43	1.60–1.90	0.15–0.30	—	—	—	—
4023	0.20–0.25	0.70–0.90	0.15–0.30	—	—	0.20–0.30	—
4028	0.25–0.30	0.70–0.90	0.15–0.30	—	—	0.20–0.30	—
4047	0.45–0.50	0.70–0.90	0.15–0.30	—	—	0.20–0.30	—
4118	0.18–0.23	0.70–0.90	0.15–0.30	0.40–0.60	—	0.08–0.15	—
4130	0.28–0.33	0.40–0.60	0.15–0.30	0.80–1.10	—	0.15–0.25	—
4140	0.38–0.43	0.75–1.00	0.15–0.30	0.80–1.10	—	0.15–0.25	—
4150	0.48–0.53	0.75–1.00	0.15–0.30	0.80–1.10	—	0.15–0.25	—
4320	0.17–0.22	0.45–0.65	0.15–0.30	0.40–0.60	1.65–2.00	0.20–0.30	—
4340	0.38–0.43	0.60–0.80	0.15–0.30	0.70–0.90	1.65–2.00	0.20–0.30	—
4620	0.17–0.22	0.45–0.65	0.15–0.30	—	1.65–2.00	0.20–0.30	—
5120	0.17–0.22	0.70–0.90	0.15–0.30	0.70–0.90	—	—	—
5145	0.43–0.48	0.70–0.90	0.15–0.30	0.70–0.90	—	—	—
6150	0.48–0.53	0.70–0.90	0.20–0.35	0.80–1.10	—	—	0.15–0.25
8620	0.18–0.33	0.70–0.90	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25	—
8630	0.28–0.33	0.70–0.90	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25	—
8640	0.38–0.43	0.70–0.90	0.15–0.30	0.40–0.60	0.40–0.70	0.15–0.25	—

Alloying Elements in Steels

The family of steels is created by several factors:

- The steelmaking process
- Addition of alloying elements
 - for “conditioning,” e.g., deoxidizing, grain size control
 - for mechanical properties, e.g., strength, ductility, toughness
- The rolling and forming processes
- Heat treatment
- Combinations of the above

Modern steelmaking technology permits very close control of undesirable elements such as sulfur and phosphorous, and precision additions of desired elements in order to assure the desired properties.

Alloying elements are added to increase strength, to achieve higher strength in thick sections, (gener-

ally described as *hardenability*), to increase ductility and toughness, to provide resistance to softening at elevated temperatures, to resist corrosion, and for other purposes. Table 2.7 is a brief summary of the effects of common alloying elements at the levels used in carbon and low-alloy steels. These effects can be quite different at other levels, e.g., in the steels covered here, chromium is used for strengthening and elevated temperature performance. At much higher levels, it promotes corrosion resistance in stainless steels.

Most structural alloys have been developed with comprehensive weldability considerations, but in general, as the strength and thickness of a material increase, the level of care and control required to assure a satisfactory weld increases rapidly. Some materials have intentional additions of sulfur or lead to enhance their performance in machining operations. So-called *free-machining steels* are often quite difficult to weld, and special techniques may be required to make satisfactory welds.

Table 2.6—Properties for Steel and/or Welds

Tensile Properties (Refer to Figures 2.7, 2.8, and 2.9)	U.S.	SI (Metric)
Strength —this term is always quoted or specified in units that reflect a (tension) load over a specific area. Following are common terms for strength in the U.S. Customary Units and International (metric) Units.	psi (pounds/square inch)	MPa (newtons/square meter)
Yield Strength —the load at which the material takes a permanent “set,” i.e., plastic deformation has begun. In a tensile test, this is customarily defined as the point at which 0.2% (plastic) deformation has occurred.	psi	MPa
Tensile Strength (or Ultimate Tensile Strength)—the point in loading where the maximum unit load is recorded. Because the specimen will normally “neck down” and reduce its cross-sectional area before failing, the load at failure may actually be lower. Also, since some reduction in area will likely have occurred prior to reaching the maximum load, the number isn't accurate, but it is the one normally used.	psi	MPa
Elongation —a measure of the “stretch” of a tensile specimen from initial loading to failure. It is the percentage change in the “Gage Length” in Figures 2.7 and 2.8.	%	%
Reduction of Area —this indicator of ductility is the reduction of cross section from the original to the area of the tensile test specimen when it breaks. Figure 2.8 illustrates how a tensile specimen typically “necks down” before failure. Reduction in Area is calculated as $1 - (\text{Area at } D_f / \text{Area at } D_s) \times 100$.	%	%
Toughness —a term intended to measure the resistance of the material to catastrophic failure when under load. A variety of tests and indicators have been developed to provide assurance that a structure will not fail in a catastrophic, i.e., brittle or glasslike manner, but the most common is the Charpy V-Notch Test. See Figure 2.10. This test is often conducted over a range of temperatures to determine the tendency of a structure to become “brittle” at low temperatures. (See “Transition Temperature” definition on page 6.)	ft-lb	Joules

Table 2.7—Effects of Common Alloying Elements at Levels Used in Carbon and Low-Alloy Steels

Common Alloying Elements	Range in Carbon and Low-Alloy Steels (%)	Effect
Carbon (C)	0.01–0.8	Most powerful hardener
Manganese (Mn)	0.02–2.5	Deoxidizes, ties up sulfur, increases hardenability
Silicon (Si)	0.3–2.0	Strong deoxidizer, increases hardenability
Chromium (Cr)	0.1–3.0	Strongly increases hardenability, improves high temperature strength
Nickel (Ni)	0.25–5.0	Promotes thick section hardenability
Molybdenum (Mo)	0.05–1.5	Strong hardener, improves creep resistance
Niobium (Nb)	0.01–0.15	Strong hardener, “micro alloying” agent
Vanadium (V)	0.05–0.10	Very strong hardener, “micro alloying” agent
Copper (Cu)	0.1–1.2	Moderate hardener, high levels promote corrosion resistance, can cause weld cracking sensitivity
Sulfur (S)	0.005–0.04	Undesirable, can result in solidification cracking
Phosphorus (P)	0.005–0.04	Undesirable, can promote embrittlement