

Chapter 7. Welding Metallurgy

This chapter provides an introduction to metallurgical concepts that influence welding processes and welding quality control. Special emphasis is placed upon the terms often heard and used during inspection activities. However, in this introductory material, simplified definitions and explanations will at times be employed.

Mild Carbon Steel

Mild carbon steels contain iron plus small quantities of other elements. The five most common and their quantitative limits in a representative grade, AISI/SAE 1020 steel, are:

Carbon (C)	0.18-0.23%
Manganese (Mn)	0.30-0.60%
Silicon (Si)	0.30% max
Phosphorous (P)	0.040% max
Sulfur (S)	0.050% max

When such a steel is slowly cooled and subsequently viewed under a metallurgical microscope, a network of light-colored grains will be visible (Fig. 7.1). The grains are outlined by much darker grain boundaries and can contain islands of darker materials.

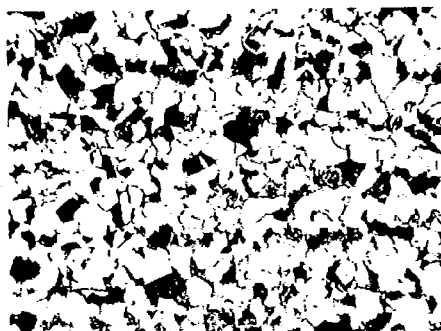


Fig. 7.1—Fine grain structure of mild carbon steel in annealed condition showing grains of ferrite and pearlite

When this material is viewed at 100× magnification, grain size can be measured. While ASTM provides comparison charts (ASTM Specification E112) for such measurements, an approximation can be made by determining the average number of grains per linear inch at this 100× magnification. On this basis, seven grains per inch approximates ASTM grain size 7.



Fig. 7.2—Typical thin-layered structure of pearlite at 1500× (before reduction)

The light part of the grain is called ferrite. It is nearly pure iron since it can only absorb a maximum of 0.025% C. The dark grain boundaries are predominantly iron carbide (Fe_3C). This iron-carbon phase is called cementite. The darker islands are mixtures of ferrite and cementite that form thin layers called pearlite (Fig. 7.2). The amount of cementite and pearlite is proportional to the carbon content. Due to the large quantity of ferrite in weldable grades of carbon steel, such steels are referred to as ferritic steels.

Further magnification of this steel would reveal a crystalline structure within each grain. This structure contains the relative orientation of the iron atoms as shown in Fig. 7.3. Ferrite and cementite have the body-centered cubic

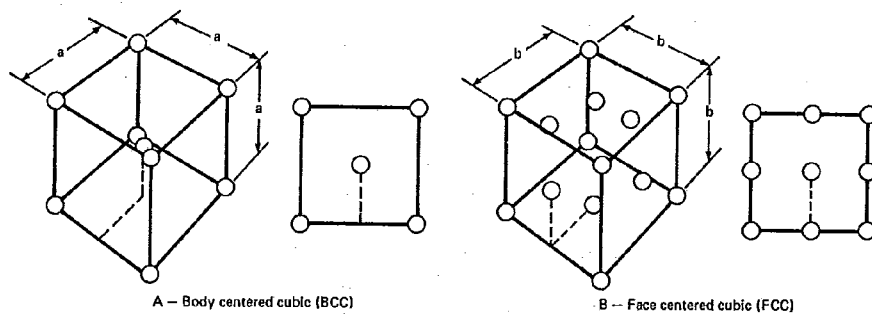


Fig. 7.3—Two common crystal structures in steel

(BCC) structure as shown in Fig. 7.3A, while the orientation of some other phases (such as austenite which will be discussed subsequently) is face-centered cubic (FCC) as shown in Fig. 7.3B. Most of the atoms that make up these crystals are iron, but if alloys are added, some of these iron atoms are replaced by the alloying elements. At other times the alloy atoms are squeezed into the space between the normal crystal pattern. These changes in crystal structure or phases give ferritic steels the somewhat unique characteristic of being able to change their mechanical properties by different heat treating cycles.

Slowly cooled mild carbon steels have a uniform microstructure with the lowest tensile strength and the highest ductility. These can be changed by heat treating, mechanical working, alloy or carbon additions, or combinations thereof. The effect of heating and cooling is of particular interest to welding, since part of the metal is heated to the melting point in most welding processes.

When mild carbon steel is heated during welding or heat treating, the first important change, a predominantly mechanical one, starts at about 950°F (500° C). The change lowers the yield strength of the steel; some of the residual stresses caused by cold working or weld shrinkage are relieved, and the material is softened.

A major metallurgical change occurs when ferritic steel is heated above its lower transformation temperature, often referred to as the A_1 temperature. For all carbon steels this temperature

is 1333° F (720° C). When heated above A_1 , both of the body-centered cubic (BCC) phases (ferrite and cementite) begin to transform into a face-centered cubic (FCC) phase called austenite. The temperature that must be reached to complete this transformation, which is referred to as upper transformation temperature or A_3 , depends upon the specific chemical composition of the steel. For a mild carbon steel (e.g., AISI 1020), A_3 is at about 1560° F (850° C).

This austenite is retained until melting starts at 2535° F (1390° C). However, in the austenitic range grains can increase in size. The higher the temperature and the longer the holding time, the larger the grain size. Since some of these grains retain their size after cooling, the largest grains in a weldment are located in the base metal immediately adjacent to the fusion line of the weld.

It is important to note that these metallurgical changes occur every time a weld bead is deposited. Figure 7.4 shows that a temperature range exists during welding that permits ferrite, cementite, austenite, and liquid metal to exist in close proximity. The base metal adjacent to the weld, which has not become molten but has gone through some metallurgical changes, is referred to as the heat-affected zone or the HAZ.

As the welding arc travels along the weld seam or is extinguished to change electrodes, or upon completion of the weld, the heated areas are free to cool. Two major events, one mechanical and one metallurgical, occur during this cooling operation:

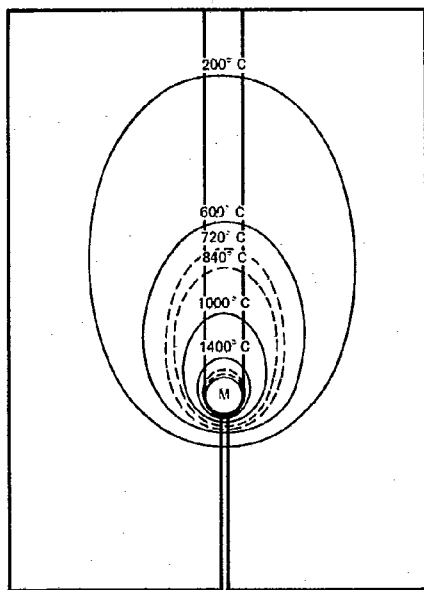
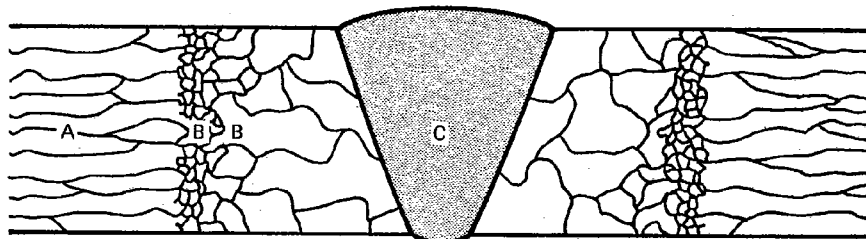


Fig. 7.4—Temperature distribution during welding

- (1) Residual stresses and distortions are caused by local weld area shrinkage during solidification and cooling. This is a mechanical process that is discussed in another chapter.
- (2) The metallurgical process described earlier will be reversed as the steel cools through the

transformation range. If slow cooling can be obtained, the transformation cycle upon cooling will be the reverse of the transformation cycle upon heating. Although grain size may be changed as shown on Fig. 7.5, the HAZ will contain a combination of ferrite, pearlite, and cementite and thus will be similar to the original soft base metal.

Cooling rates depend upon the total heat input, including preheating, and a combination of material size, thickness, and thermal conductivity. Since the mass melted during welding is usually quite small when compared to the adjacent base metal, rapid cooling rates are expected. This can be easily observed by noting that the weld bead will cool from the molten state to black steel at about 1200° F (650° C) in just a few seconds. When very low carbon steels (e.g., rivet steels with less than 0.10% C) are cooled rapidly, nearly all the austenite will transform to ferrite and remain soft and ductile. This is why many types of welding electrodes are designed with relatively low carbon content. However, the mild carbon steels commonly used for piping, pressure vessels, and structures contain between 0.18 and 0.35% carbon. When they are cooled, an iron-carbide phase must be formed. As stated earlier, slow cooling will permit the formation of pearlite. However, the rapid cooling rate associated with welding tends to produce harder and less ductile metallurgical structures or phases called martensite and bainite. Both have a needle-



- A — Cold worked area (elongated grains)
- B — Recrystallized area or equiaxed grains with coarsest grains adjacent to weld
- C — Weld area (cast structure or columnar grains)

Fig. 7.5—Crystal structure of cold rolled steel in weld area

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like or acicular structure as shown for martensite in Fig. 7.6.

While a certain amount of martensite and bainite is normally unavoidable, their amount and their effect can be minimized by proper base metal and electrode selection, welding technique, and preheating and interpass temperatures. The need for such actions becomes more important as material thickness or carbon content, or both, increase. Thicker base metal removes heat in less time from the weld area and thus increases the rate of cooling. A unit called "carbon equivalent" (CE) is often employed to predict the combined effect of carbon and manganese upon the tendency to form martensite. For mild carbon steel, the carbon equivalent is most commonly expressed as:

$$CE = \%C + \frac{\%Mn}{4} \text{ or } CE = \%C + \frac{\%Mn}{6}$$

The higher the CE and the thicker the material, the greater the need for preheating.

As the CE, the wall thickness, or both increase, preheating and carefully planned welding techniques are insufficient to limit the amount of martensite formation. This introduces the need for postweld heat treatment (PWHT). In most cases, this is accomplished by heating the weldment between 950° F (500° C) and the lower

transformation temperature of 1333° F (723° C). Within that temperature range, the yield point of the material drops considerably. This permits locked in or residual stresses to be lowered; at the higher temperatures within that range, some of the martensite will be softened. The metallurgist refers to the second effect of this operation, which softens the steel, as "tempering." This explains why the PWHT operation is often called "stress relieving" by the welder and "tempering" by the metallurgist.

Other PWHT's are sometimes employed. Most of them involve heating the weldment above the upper transformation temperature and holding it long enough in that range to achieve complete transformation into austenite. The specific name assigned to this heating treatment depends on the cooling rate. If the material is cooled: (1) slowly, as in a furnace, it produces the softest or "dead soft" steel and is called annealing; (2) at a moderate rate, as in air, it is called normalizing; and (3) at an accelerated rate, as in water, it is called quenching. The latter two increase strength, toughness, and other mechanical properties. However, to limit these properties and especially to prevent brittle material, normalized or quenched steels usually require a second heat treatment. This is performed at lower temperatures, is followed by slower cooling, and is called tempering. Many variations and combinations of heat treating cycles are used by industry. A full discussion of this topic is beyond the scope of this publication.



Fig. 7.6—Martensite showing needle-like or acicular structure (500× before reduction)

Low Alloy Steels

To increase strength, notch ductility, corrosion resistance, and other specific properties, alloys are often added to mild carbon steels. The welding engineer must select electrodes capable of matching the mechanical properties and the chemical composition of these alloy base metals in order to achieve a uniform structure.

Although the addition of such elements as chromium, nickel, molybdenum, copper, and vanadium can significantly change the properties of the steel, the basic metallurgical concepts are similar to those that apply to mild carbon steel. A combination of ferrite and alloy-iron-carbon

phases can produce weldable materials with adequate ductility. Softening will start between 1000° F (540° C) and 1250° F (680° C), depending upon the specific composition. For alloy steels, the lower transformation temperature is higher than the 1333° F (720° C) that applies to carbon steel. For many (but not for all) alloy steels, the safe maximum PWHT temperature below the transformation range is 1475° F (800° C). Since this temperature varies some for each low alloy steel classification, optimum PWHT temperatures should be established and documented for each. For several alloy steels, it is not uncommon to anneal the welded component at much higher temperatures.

During welding, part of the alloy steel will pass through the lower and the upper transformation temperatures and thus will be fully austenitic. In this respect, there is little difference between mild carbon and low alloy steel. Also, the cooling rate for low alloy steels is the same as the rate for mild carbon steels. However, the alloy material is more susceptible to hardening, to embrittling, and subsequently to cracking, since martensite can form at slower cooling rates. The ability of the alloy steel to form such martensite can again be expressed as a "carbon equivalent" (CE) for which there are many similar formulas that include many elements in addition to carbon and manganese. One of these showing the effect of such alloy additions is:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo - \%V}{5} + \frac{\%Ni + \%Cu}{15}$$

With a high CE, even a relatively slow cooling of the weldment will produce large quantities of martensite and bainite. Preheating, while essential for nearly all alloy steel welds, often fails to retard the cooling rate sufficiently; however, it can prevent cracking during fabrication. Thus, PWHT is mandatory for many alloy steels to restore sufficient ductility prior to exposing the assemblies to service conditions.

Hydrogen and Steel

Carbon and low alloy steels can absorb con-

siderable quantities of hydrogen at elevated temperatures. However, as the steel cools, it can retain less and less hydrogen in solution; thus, it ejects the excess hydrogen.

When steel is held at elevated temperatures and during slow cooling, the small hydrogen atoms can escape by diffusion to the atmosphere. However, rapid cooling, often associated with welding, tends to trap the atoms, which will then collect in small voids. As more hydrogen enters these voids, the pressure will build up. If the material is ductile, the void can grow slightly and thereby reduce the pressure. In a brittle material and in materials with high residual stresses, the growth of voids can easily propagate into cracks. This phenomenon is known by such terms as hydrogen cracking, underbead cracking, or delayed cracking. Steels with higher strengths and higher alloy contents are more susceptible to hydrogen-related cracking.

Hydrogen can enter the weld metal by release from moisture or organic matter on the material surface, in the welding atmosphere, or within the welding consumables (e.g., electrodes, fluxes, and gases). In fact, coatings of some electrodes (such as E6010) contain hydrogen-rich cellulose; some of this hydrogen can and will enter the steel during welding.

Thin walled, mild carbon steel weldments are practically immune to underbead cracking and thus permit the use of cellulose coated electrodes. However, carbon and alloy additions to steel increase strength and, therefore, the probability of hydrogen-related defects. This can be minimized by establishing and enforcing welding procedures that prevent hydrogen from entering the weld area and by taking steps that permit hydrogen to escape. Typical methods to achieve these aims include:

- (1) Thorough cleaning and drying of the base metal
- (2) Pre-heating and maintaining minimum interpass temperatures
- (3) Exclusive use of low hydrogen electrodes or hydrogen-free welding processes
- (4) Proper drying and storing of welding electrodes, fluxes, and gases and proper maintenance of equipment such as wire feeders
- (5) Postweld heat treatment

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The degree to which such precautions are needed varies for different alloy steels.

Austenitic Stainless Steel

The most common austenitic stainless steels contain between 18 and 25 percent chromium and between 8 and 20 percent nickel as primary alloying elements. In product forms such as plates, forgings, and electrodes, they are classified by a three-digit numbering system and can be easily recognized since the first digit is a "3"; the detailed chemical composition is governed by the last two digits. In view of these two facts, these materials are often referred to as "austenitic chromium-nickel steels" or "300-series steels."

The 300-series steels have many chemical and metallurgical characteristics that clearly distinguish them from ferritic steels such as mild carbon or low alloy steels. Specifically, the 300-series steels:

- (1) Are more corrosion resistant in most environments
- (2) Have higher tensile and creep strength at elevated temperatures
- (3) Are not magnetic or only slightly magnetic
- (4) Cannot be hardened by heat treatment

Austenitic stainless steels do not undergo the normal phase changes that apply to ferritic steels. While mild carbon steel is austenitic and non-magnetic at elevated temperatures, it will transform into ferrite, pearlite, martensite, and other phases as it is cooled through the transformation range.

However, when austenitic stainless steel is cooled, all or nearly all of the material is retained as austenite at room temperature. Without phase changes, no hardening will occur. Thus, hard areas are not found in the heat affected zone (HAZ) of 300-series stainless steels. This reduces the need for preheating and postweld heat treating.

This chapter will not discuss the different grades of stainless steels and the optimum application of each. However, when these materials are welded, two specific items must be considered: (1) carbide precipitation or sensitization, and (2) microfissuring, ferrite content, and sigma formation.

The corrosion resistance of the 300-series stainless steels depends upon the addition of various alloys of which chromium is of primary importance. If the alloy is heated to the so-called "sensitization range" of 800-1600° F (425-870° C), some of the chromium can combine with any carbon that is available and form a chromium-rich precipitate. Whenever this occurs, as it can during welding, less chromium is available to resist corrosion. This is especially serious if the corrodent is an acid (for example, see Fig. 7.7).

This sensitization can be overcome by any one of the following actions:

(1) Heat the steel after welding to about 1900° F (1050° C) to dissolve the carbides and cool rapidly through the sensitization range. This is called "solution annealing." It is practiced in steel and pipe mills, but it is not easily adapted to shop assemblies and field erection.

(2) Employ 300-series steel with low carbon content. By limiting the percent carbon to a maximum of 0.03 or 0.04, these so-called "L" grades (e.g., 308L, 316L, etc.) also limit the amount of carbides that can form and thus the amount of chromium that can be depleted.

(3) Stabilize the material by adding scavengers in sufficient quantity. Elements like columbium and titanium will combine preferentially

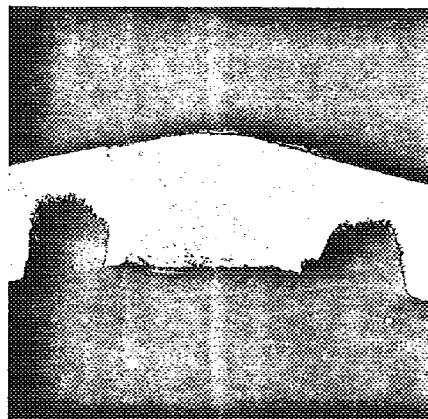


Fig. 7.7—Corrosion attack of sensitized stainless steel in acid environment

with the carbon. This will retain the chromium for corrosion protection even when reaching the sensitization range during welding or other operations.

It was stated earlier that 300-series steels are predominantly austenitic. Pure austenite has excellent mechanical and corrosion-resistant properties. However, its ability to absorb impurities without cracking during solidification and cooling from elevated temperatures is limited. Low-melting impurities may be forced to the grain boundaries. Excessive amounts weaken these grain boundaries, creating the possibility of microscopic grain boundary flaws called "microfissures" (shown on Fig. 7.8). This condition is of special importance when the solidification is limited to small areas under the high restraint associated with welding.

One method of reducing microfissuring is to disperse these impurities among disconnected grain boundaries that surround islands of a second phase. This is accomplished by modifying the chemical composition to create small percentages of ferrite. Ferrite can absorb many impurities, and the ferrite islands are dispersed throughout the microstructure. While this can cause a slight decrease in corrosion resistance, it will definitely reduce microfissuring tendencies.

However, too much ferrite can cause another problem. It can transform into what the metallurgist calls "sigma phase" when the metal is heated to temperatures associated with welding and heat treating. Since this very brittle constituent was transformed from the evenly dispersed ferrite, small amounts of sigma will embrittle large areas of stainless steel.

The above paragraphs indicate that both minimum and maximum limitations on ferrite are desirable to prevent microfissuring and sigma formation. Many modern electrodes are designed to produce deposits with ferrite within a specific percentage range or within an equivalent "ferrite number" range, such as 4 to 10 or 5 to 15, to meet individual needs. For critical weldments, the amount of ferrite can be measured as a scheduled inspection operation by using a magnetic gage or by analyzing the results of a complete chemical analysis. Details of the magnetic method can be found in AWS A4.2-74, Standard Procedures for Calibrating

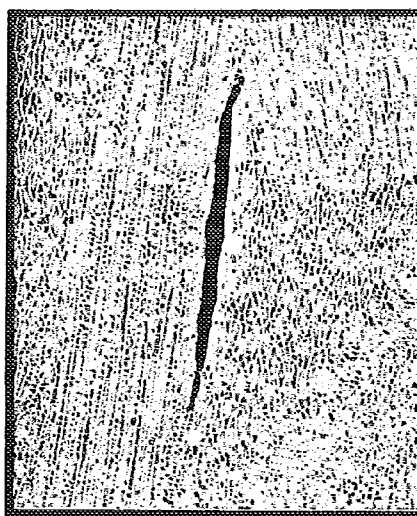


Fig. 7.8—Microfissure in austenitic stainless steel (100×)

Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal.

Laminations and Lamellar Tearing

While the terms "lamination" and "lamellar tearing" sound quite similar, occur primarily in the same places, and are likely to produce similar failures, they represent two distinctly different phenomena.

Laminations are inclusions or separations that exist in the material as the result of impurities (such as sulfates or silicates) that segregate during ingot solidification and are subsequently flattened during rolling or hot working applications. Thus, they are most likely to occur at or near the center of plates as indicated on Fig. 7.9. The probability of plates containing laminations increases with the thickness of the plate and decreases with increased cleanliness of the steel. Laminations are seldom, if ever, found in castings.

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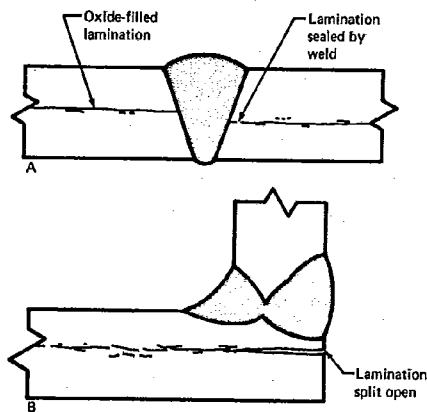


Fig. 7.9—Laminations in welded assemblies

Lamellar tearing occurs during a welding operation and is not a pre-existing condition. For most steel plates, the percent elongation is approximately the same in the direction of rolling and in the transverse direction ("A" and "B" in Fig. 7.10).

However, in the through-thickness or short-transverse direction ("C" in Fig. 7.10), the percent elongation can be considerably lower. If this elongation is very low, it may not be able to withstand the high shrinkage stresses associated with weld solidification and cooling. Figure 7.11 illustrates the kind of joint that becomes a likely candidate for lamellar tearing if it does not possess good through-thickness elongation properties. These tears usually remain subsurface, occur adjacent to the HAZ, and exhibit a terrace type separation. On this basis, lamellar tearing can be defined as a separation of the base metal due to welding stresses.

It is quite difficult and often impossible to predict susceptibility to lamellar tearing in any steel plate, but any design that exerts shrinkage stress in the through-direction of a plate is a likely candidate for such tearing. It again appears that castings are immune to such problems.

Other Metallurgical Considerations

The soundness of a weld during fabrication and during its service life is influenced by many metallurgical considerations. While most are beyond the scope of this book and the activities of an inspector, a few concepts have been highlighted below.

Metallurgical Inclusions: Many elements are added to steel or other base metals to produce certain desirable properties. However, certain elements may severely deteriorate the base and weld metal properties by penetrating into the molten weld metal. These include the following elements that may be in contact with a metal during welding related operations:

- (1) Copper (in the form of contact tips and magnetic particle testing prods)
- (2) Lead (in the form of caulking or lining)
- (3) Sulfur (in the form of molecular sulfur that has been deposited while the equipment was in service)
- (4) Zinc when welding austenitic stainless

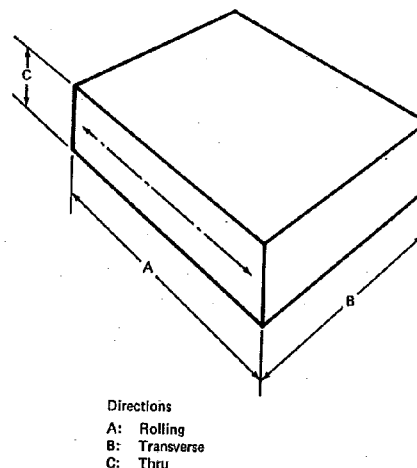


Fig. 7.10—Terminology related to rolling direction

steel and carbon steels (in the form of galvanized components or cathodic protection equipment)

Fatigue: Fatigue cracking occurs in service and not when the weld is made. However, the manner in which the weld is made may influence fatigue life of the product. Since any irregularity in shape or any notch (such as a roll-over or undercut) may be undesirable, special grinding or machining of welds is sometimes specified by the designer to improve the fatigue life of his component.

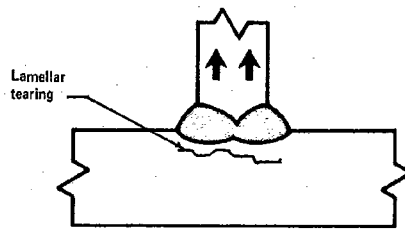


Fig. 7.11—Joint showing typical lamellar tear resulting from shrinkage of large welds in thick material under high restraint