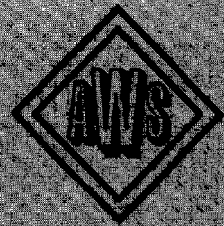


CHAPTER 6:**WELDABILITY, WELDING
METALLURGY, AND
WELDING CHEMISTRY****Introduction**

A weld joint is the functional unit basic to any welded structure, and the key base metal property is weldability. The better the weldability of a metal, the easier it can be fabricated into a suitably designed structure that will perform satisfactorily. Weldability is determined by several factors, including:

- Welding metallurgy
- Welding chemistry
- Joint surface condition
- Joint geometry

Welding metallurgy deals with the changes that occur in a metal when acted upon by various mechanical and thermal effects of a welding process. It considers the basic atomic structure of metals and how that structure can be affected by forces and temperature. Metals' atomic structures have a pronounced effect on their resulting mechanical properties. Consequently, we will be able to establish relationships between the metallurgical treatments given metals (preheat, postheat, stress relief, etc.) and the mechanical properties which result.

Welding chemistry deals with the chemical interaction between the base metals, filler metals and other chemicals present at the joint during the welding process. The ability of the base metal and filler metal to fuse together without adverse chemical effects is an important factor in determining weldability.

The final factors affecting weldability are referred to as joint surface condition and joint geometry. The joint surface condition factor includes the effects of different amounts of surface roughness and cleanliness of the joint. The shape of the joint edge geometry will also have an effect on a metal's (or perhaps a joint's) weldability. The amount of joint restraint can also have an effect on weldability.

Although weldability problems are supposed to be solved by engineers, it may be that the inspector will be the first person to sense that a weldability problem exists. Welders do not generally make poor welds on purpose; instead, they usually struggle to make good welds, and to correct faults. Whenever a rejection is encountered, its cause should be sought out and corrections made. Defects that are not welder-oriented, or are repetitive, should be noted and reported for corrective action.

Why, then, is there a need to study weldability, when the welding inspector's job entails no responsibility for the ease or difficulty of making the welds being inspected? Is not weldability something the engineer should study, to improve the chances that the weld design will be worth inspecting?

The answer is: Sometimes the best choice the engineer can make is a compromise that will still leave the welding inspector examining welds made in steels of poor weldability. The welding inspector will then be vulnerable to overlooking unexpected discontinuities if not prepared to give special attention to those welds that are extra prone to cracking, to welds that may crack the

6-2

base metal beneath the surface, and to welds that may significantly reduce the corrosion resistance of the base metal's heat affected zone (HAZ). It is important the welding inspector have knowledge of these types of weldability problems to better do his/her inspection function. Understanding the basics also helps when discussing problems with engineers.

Engineers should know the weldability of the metals they select; many problem alloys are listed in technical references on welding metallurgy. The topic of weldability for various steels is covered in great detail in the book, *Weldability of Steels*, published by the Welding Research Council and available through AWS. The AWS "Welding Journal" is also an excellent source for this type of information, since it includes many research papers on the subject of weldability.

An example of a code reference to the weldability of a metal is found in AWS D1.1, *Structural Welding Code- Steel*. The particular reference has to do with the welding of certain high strength, low alloy, quenched and tempered steels (ASTM A514 and ASTM A517). The precaution is clearly stated in several paragraphs in Sections 8, 9 and 10: "Final weld inspection of these materials must not occur until at least 48 hours after welding is completed and the base metal has cooled to room temperature." The reason for this is that these steels are susceptible to underbead cracking, a delayed cracking problem, which premature inspection will not discover.

Welding Metallurgy

Metallurgy is the science which deals with the internal structure of metals and the relationship between those structures and the properties exhibited by metals. When referring to welding metallurgy, the real concerns are about the various changes that occur in metals when joined by welding. From a welding standpoint, there are several topics with which welding engineers are concerned:

Solids and liquids properties

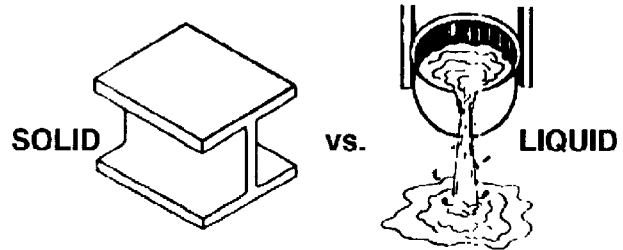
Diffusion

Solid solubility

Melting and freezing

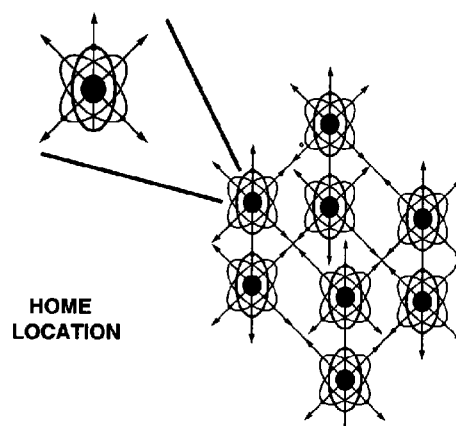
Thermal expansion

Thermal treatments (e.g. stress relief)



Solids Versus Liquids

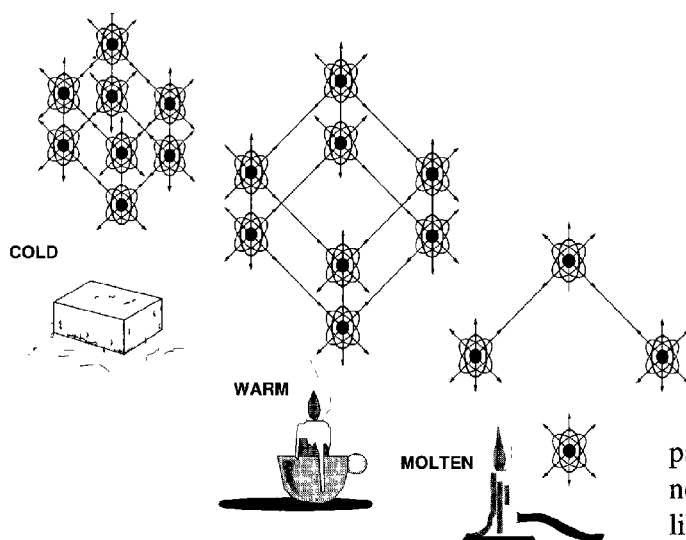
Since the topic of interest here is welding, the following discussion will be related to the solid (metallic) state, and the liquid (molten) state. The primary difference between these two states of matter in metals is the amount of energy contained in each. The liquid metal contains a much higher level of internal energy than the solid metal. Structurally, the major difference is that for solid metals, the atoms are in a fixed position relative to each other, while in a liquid, the atoms are free to move in relation to each other.



In the solid state, each atom has a specific 'home' position with respect to all the other atoms adjacent to it. These atoms are aligned row upon row, layer upon layer, in a three-dimensional,

symmetrical, crystalline structure, or pattern. These 'fixed' atoms are held in place by the attraction and repelling forces of their neighboring atoms. Each atom nucleus has a cloud of encircling electrons to complete its atomic structure. This overall atomic configuration gives metals in the solid state their metallic luster and determines their physical, mechanical, chemical and electrical properties.

While occupying these 'home' positions in the solid state, the atoms are vibrating or oscillating about their home position. The amount of atom movement is directly proportional to the metal's temperature. As the metal temperature increases, the movement of the atoms becomes larger and faster. Eventually, as temperature continues to increase, the internal energy increases to the point where the individual atoms break away from one another and move freely in the liquid state. This 'breakaway' occurs at the melting point of the metal.

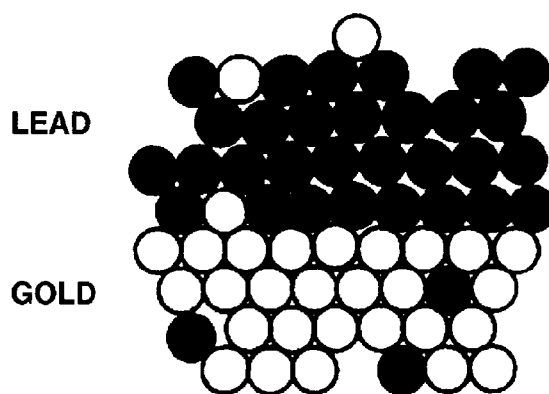


Diffusion

We have previously noted that atoms in the liquid state can move about easily with respect to each other; however, under certain conditions, even atoms in the solid state can change positions. In fact, any atom may 'wander' away, step by step,

from its home position. These changes of atom position in the solid state are called diffusion.

An example of diffusion is shown if smooth, flat bars of lead and gold are clamped tightly together. If they are clamped together at room temperature for several days, the two sheets of metal remain attached when the clamps are removed. This attachment is due to the fact that atoms of lead and gold have each migrated, or diffused, into the other metal, forming a very weak metallurgical bond. This bond is quite weak, and the two metals can be broken apart by a sharp blow at their joint line. If the metals' temperatures are increased, the amount of diffusion increases, and at a temperature above the melting point of both, complete mixing occurs.



Another example of diffusion occurs when hydrogen, a gas, is allowed in the vicinity of molten metal, such as a weld. The most common source of hydrogen is moisture (H_2O), or contamination on the surfaces of the parts to be welded. Many of the contaminants normally found on metals are organic compounds, like oil, grease, etc., and they contain hydrogen in their chemical makeup. The heat of welding will break down the water or organic contaminants into individual atoms, which includes the hydrogen atom (H^+). The hydrogen atoms are quite small, and they can easily diffuse into the base metal structure. As they enter the base metal, the hydrogen atoms often re-combine into the hydrogen molecule (H_2), a combination of two

atoms of hydrogen, which is much larger than a single atom of hydrogen. The larger molecules often become trapped in the metal at discontinuities such as grain boundaries or inclusions. These hydrogen molecules, because of their larger size, can cause high stresses in the internal structure of the metal, and for metals of low ductility, can cause cracking. Hydrogen cracking is often referred to as 'underbead' or 'delayed' cracking.

The primary cure for hydrogen cracking problems is to simply eliminate the source of hydrogen; the first step is to thoroughly clean all surfaces to be welded. Another approach is to specify the 'low hydrogen' electrodes for use on carbon and low alloy steels. These low hydrogen electrodes are specially formulated to keep their hydrogen content quite low, but they do require special handling to avoid moisture pickup after opening the sealed shipping containers. Preheating the base metals is also effective in eliminating hydrogen pickup because hydrogen will diffuse out of most metals at temperatures of 200 - 450 degrees F. The methods noted above can all aid in reducing the possibility of hydrogen cracking in those metals which are susceptible.

Solid Solubility

Most of us are familiar with the normal solubility of solids into liquids. Adding a spoonful of salt to a glass of water and stirring will dissolve the salt. However, most of us are not familiar with one solid dissolving into another solid. In the example given above with the lead and gold, the two metals were diffusing through solid solution into each other. And, returning to our example of salt and water, if additional salt is added, we find that some of it will not dissolve regardless of how much we stir. What has happened is that for that amount of liquid, and its temperature, we reach a 'critical solubility limit'. No amount of stirring will dissolve any more salt. In order to dissolve more salt, the liquid volume would either have to be increased, or its temperature raised. Thus we

see that for a solid dissolving into a liquid, there is a critical solubility limit depending on liquid volume and temperature. Metals behave similarly, except through diffusion, and they 'dissolve' into each other when both are solid.

But just like the salt and water, there are solubility limits of one solid dissolving into another and the critical solubility limit is dependent on temperature. The higher the temperature of a metal, the more dissolving of a second element will occur. Thus, we can get metals combining even when both are solid. Of course, as the metal temperatures are raised, the amount of diffusion and solubility do increase.

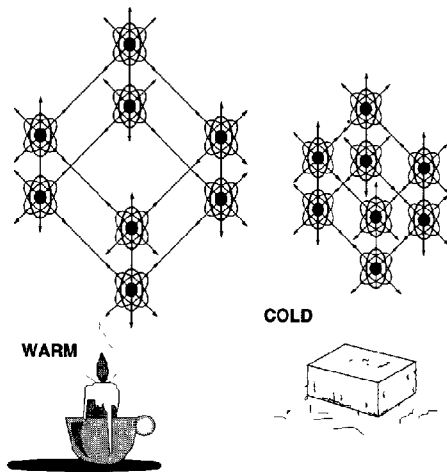
An example of a solid dissolving into another solid is a method we use for increasing the surface hardness of a steel. If the steel is packed into a bed of carbon particles, and then heated to a temperature of about 1600 - 1700 degrees F, which is well below the melting point of both the carbon and the steel, some of the carbon will diffuse (dissolve) into the surfaces of the steel. This added carbon in the steel's surface makes the surface much harder, and is useful for resisting wear and abrasion. This technique is commonly called 'carburizing'. The surface of steels can also be made hard by exposing the steel to an ammonia environment at similar temperatures to carburizing. The ammonia (NH_3) breaks down into its individual components of nitrogen and hydrogen, and the nitrogen atoms enter the surface. This technique is called 'nitriding'. Both of these surface hardening techniques demonstrate the diffusion and solid solubility of metals. Knowledge of diffusion and solid solubility will aid the welding inspector in understanding the importance of cleanliness in welding, and the need for proper shielding during all welding operations.

Melting and Freezing

When a metal is heated to the liquid state, atoms move about very energetically with complete mixing. The mixing action is created by convection and conduction, which occurs due to

the flow of heat from hot areas to colder areas. In welding, the mixing is also stimulated by magnetic forces, and by arc pressure, or pressure from a gas flame and movement of a welding electrode. The welder can observe this mixing as the metal swirls beneath the heat source. The result is that the atoms from the base metal mix with the atoms from the metal being added.

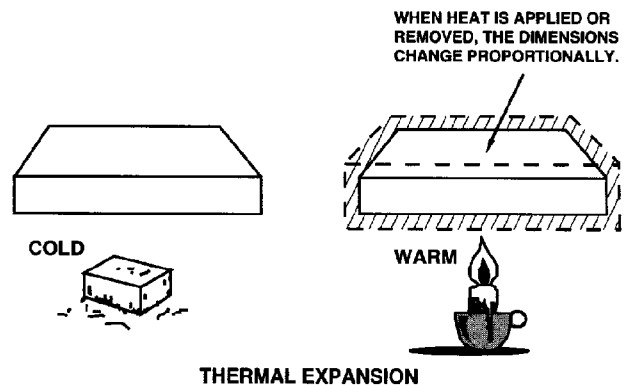
Freezing of liquid metal cannot occur until the heat source is removed and the atoms lose enough energy to 'settle down' into a metallic crystalline structure. The liquid's energy must be dissipated, in the form of heat loss. Heat is most quickly given to surrounding atoms already in the solid state. When this happens, the surrounding metal warms, and the liquid cools enough to solidify.



The initial configuration of the crystalline structure as the weld solidifies is determined by the crystalline structure of the metal already existing in the solid state. Growth continues in the same pattern if that is the natural pattern for the mix of atoms present. Atoms of a dissimilar weld composition may take their own preferred alignment shortly after the solidification has begun. Some atoms in a mixture may tend to segregate when solidifying, but in general, atoms mixed together as a liquid will form a homogeneous (consistent) weld. Segregation refers to the separation of like-atoms or phases resulting in a non-homogeneous structure.

Thermal Expansion

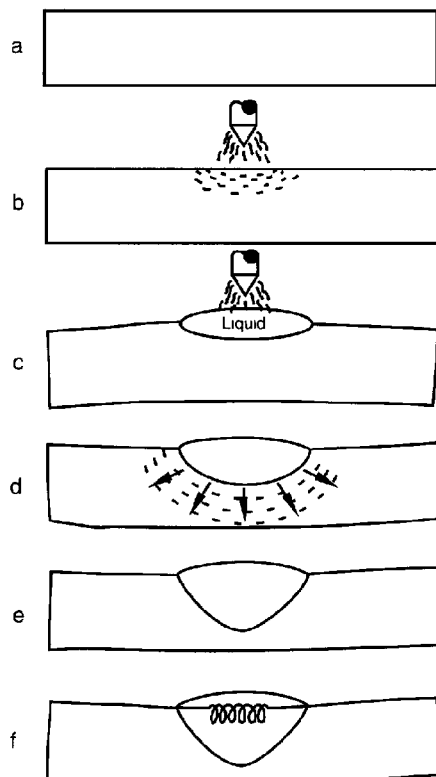
Metals expand and contract on heating and cooling because of the effects of energy on the atomic oscillations. Heating the metal puts more energy into the oscillations, which tends to move the atoms further apart. As a result, the metal expands. When the metal cools, this process is reversed and the metal contracts, or shrinks.



When heat is applied or removed uniformly from a piece of metal, the dimensions change, but stress is not induced from within because the expansion or contraction is uniform throughout. However, when the application or removal of heat is not uniform, as occurs in welding, stress is induced into the part, and some distortion may result because the hotter parts of the metal expand more than the portions at lower temperatures.

The figures on the next page illustrate the dimensional changes that occur in a straight bar (a) that is to be heated just on one side. In (b), the arc has been struck and the plate begins to heat under the influence of the arc. It is quite apparent the heating is very localized in a small spot. In (c), the heated portion expands, and because it is partially restrained by the portion of the bar that is not heated, the bar tends to bow slightly upward as shown. Since the hot part is weaker (the strength of a metal decreases as its temperature is raised) and, in fact, a small portion has actually melted, the hotter portion does not succeed in forcing the bar to bend very much. (The sketch exaggerates the amount of bending for illustration.)

In (d), the arc has been removed, and the molten portion begins to cool as the heat is conducted into the cooler portions of the bar. Heat always flows from the hot to cold sections. As cooling continues, in (e), and solidification occurs, the contraction on cooling causes the bar to bend in the opposite direction and results in a concave shape when reaching room temperature. Just from the simple act of melting a portion of the bar non-uniformly, and allowing it to cool, distortion has occurred and the bar now contains a low level of residual (remaining) stress. If the bar were restrained during the heating and cooling cycle, the residual stress would be much higher. Residual stresses can be great enough to cause cracking on cooling, or cracking in service from fatigue or corrosion stress cracking mechanisms. It is often necessary to remove these residual stresses by a post weld thermal heat treatment referred to as 'stress relief'.



Shrinkage in a weld caused by internal restraint.
Also shown is the nature of residual stress.

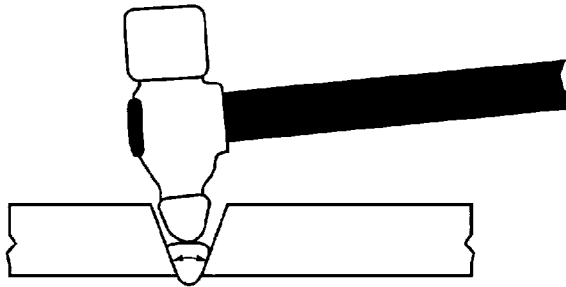
TYPICAL STRESS RELIEF HEAT TREATMENTS FOR WELDMENTS

MATERIAL	Soaking	
	°C	°F
Carbon Steel	595-680	1100-1250
Carbon - 12% Mo steel	595-720	1100-1325
1% Cr - 1/2% Mo steel	620-730	1150-1350
2-1/4% Cr - 1% Mo steel	705-770	1300-1425
5% Cr - 1/2% Mo steel (502)	705-770	1300-1425
7% Cr - 1/2% Mo steel	705-760	1300-1400
9% Cr - 1% Mo steel	705-760	1300-1400
12% Cr (Type 410) steel	760-815	1400-1500
16% Cr (Type 430) steel	760-815	1400-1500
Low-alloy Cr-Ni-Mo steels	595-680	1100-1250
2% to 5% Ni steels	595-560	1100-1200
9% Ni steels	550-585	1025-1080
Quenched & tempered steels	540-550	1000-1025

Stress Relief

The basis for stress relief is the fact that as metals are raised to higher temperatures, their mechanical strength is decreased. Typically, a common carbon steel alloy has a tensile strength of 70-80 KSI (1 KSI = 1 thousand pounds per square inch), and a yield of 30-40 KSI at room temperature. Residual stresses after welding can approach the level of the material's yield strength. When the metal is raised to its stress relieving temperature of 1100 or 1150 degrees F, the mechanical properties are greatly reduced, and the yield strength at the higher temperature typically drops to a much lower level, about 3-7 KSI. At this higher temperature, the residual stresses are much higher than the hot yield strength, and internal microstructural yielding occurs, relieving and reducing the residual stress to about the new, lower level of yield strength.

It is imperative when stress relieving a structure, that the component is heated uniformly at a prescribed rate, typically 400 degrees F/inch of thickness/hour, held for the appropriate time at its stress relieving temperature, typically one hour per inch of thickness, and then cooled uniformly, typically at a rate of 500 degrees F/inch of thickness/hour. This controlled heat-up, hold, and cool-down assures very even heating and cooling, eliminating the thermal gradients in the part and affecting a complete and thorough stress relief.



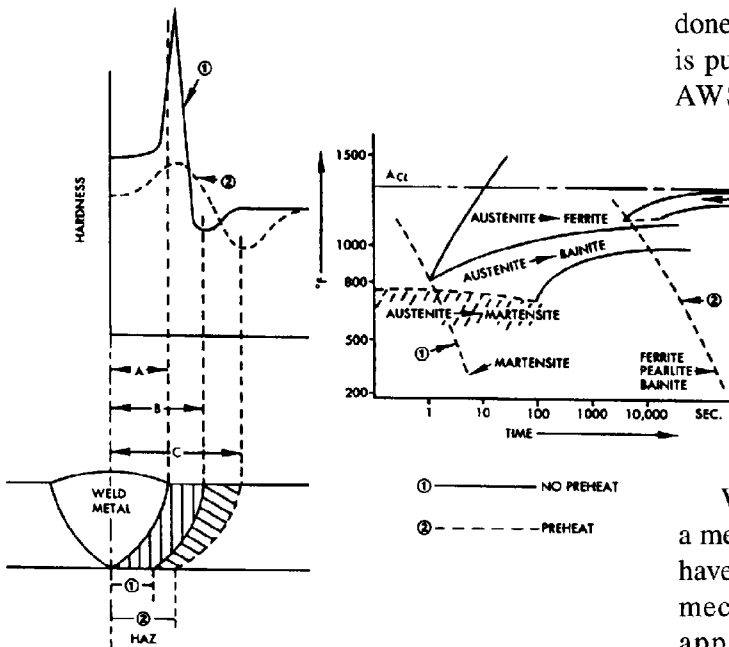
Peening the middle weld layer distributes and balances distortion.

Many of the fabrication codes require stress relief and specify the heating rates, holding temperatures and cooling rates. Stress relief can also be done using peening techniques, and vibratory stress relief. Peening is the mechanical distortion of the weld bead through mechanical means, usually when the metal is still quite hot. Peening should not be done on the root pass nor final pass of a weld, but only on the intermediate layers. Peening the root pass when it is hot can result in cracking of the weld since its size cannot withstand the mechanical distortion, and peening of the final pass can interfere with later visual

inspection or other nondestructive testing. The vibratory technique imparts a high frequency vibrational energy into the part. The table on the previous page shows typical thermal stress relief treatments for several alloys.

One technique that may be used to reduce the need for postweld stress relief is 'preheat'. Preheating a part prior to welding slows the cooling rate, and may eliminate the need for post weld stress relief. Preheating reduces the thermal gradients within a weldment and slows the cooling rate, resulting in a more ductile structure with lower residual stress. Preheat is very effective in reducing or eliminating hot cracking of many alloys. Preheat also aids in removing moisture from the part, helps remove hydrogen, and retards the formation of martensite, a hard brittle phase that forms on rapid cooling.

Preheating can be done by several methods, including gas fired or electric furnaces, electric resistance heating elements, gas torches, or high energy quartz lamps. Preheating should be done on an area much larger than just the weld zone; if done on too small an area, insufficient heat energy is put into the part, and it cools too quickly. The AWS D1.1, *Structural Welding Code-Steel*, requires that the preheat temperature be checked to assure that all parts on which the weld metal is being deposited are above the minimum specified temperature for a distance equal to the thickness of the part being welded, but not less than 3 inches, in all directions, from the area being welded.



Variation of cooling conditions in a weld as a function of preheat; diagram includes some of the property changes brought about by these conditions. Also shown is a CCT diagram for a steel, to illustrate why the cooling conditions promote the property changes.

Welds Under the Microscope

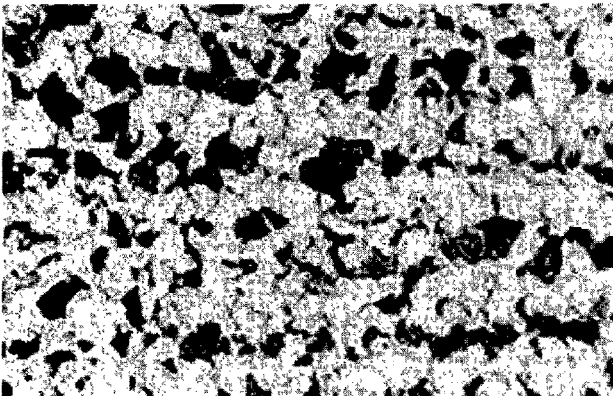
When properly prepared, and examined under a metallurgical microscope, base metals and welds have a revealing structure that correlates with their mechanical properties. A brief review of the appearance of carbon steels as seen by the metallographer will expand your appreciation of the help that a metallographic study can bring to any welding discussion.

6-8



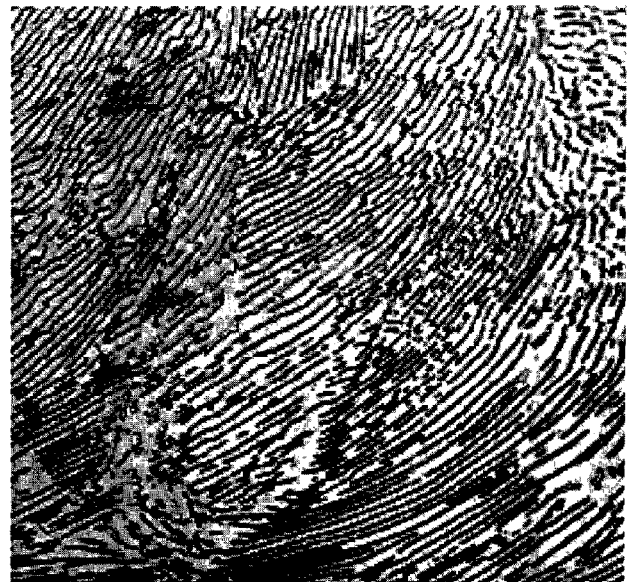
Photomicrograph of commercially pure iron, nominally called ferrite. No carbides are present, the acid etch reveals grain boundaries. The dark globules are nonmetallic inclusions.

The metallograph, a microscope designed for examining metals, shows that all metals are composed of grains, or crystals. In very low carbon iron (ingot iron), the grains are all one phase, called ferrite. Ferrite is composed of iron atoms in a body centered cubic structure (BCC), called a unit cell. A sketch of the BCC structure is shown, and you can see it is a cubic shaped structure formed by an iron atom at each corner, and one iron atom at the center of the cube. The atoms at the corners are actually shared with the adjacent unit cells.



Small grains of Ferrite and Pearlite

A medium carbon steel contains more carbon and on cooling, its structure is formed into ferrite and other phases, depending on its cooling rate. One phase formed in addition to the ferrite is an iron carbide, Fe_3C , called 'cementite'. The cementite forms in several patterns; it can occur at the grain boundaries of the ferrite grains, or in alternate bands with the ferrite grains, called 'pearlite'. Pearlite has slightly higher strength than ferrite and slightly less ductility. Pearlite is referred to as plate-like, with alternate bands of ferrite and cementite. Iron carbides can also form in a feathery form called 'bainite'. Bainite has still more strength than pearlite, with still less ductility.



Typical lamellar appearance of pearlite. 1500X Etchant:Picral

For higher carbon alloys, quenching them rapidly forms a phase which is very hard and brittle; this phase is called 'martensite'. Martensite is very strong but has very little ductility. It is necessary to 'temper' the steel after forming martensite to restore ductility and toughness. Tempering is a heat treatment that consists of re-heating the metal to temperatures ranging from 100 - 1300 degrees F. Tempering a quenched steel results in a steel having higher

strength than when annealed, with good toughness and ductility. As-quenched martensite is seldom used in components because of its brittleness and lack of toughness; tempering is almost always required. The unit structure of martensite is body centered tetragonal (BCT), and is similar to BCC except that one axis is longer than the other two, forming a rectangular unit cell.

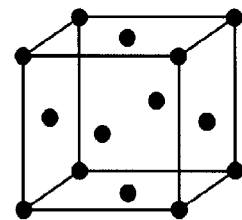


Quenched martensite (500X etched), showing acicular structure

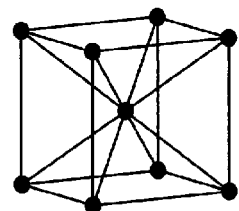
Phase Transformations

The various phases noted above are only a small part of the complexity of the metallurgy of steels. The primary reason steel is such an important part of our civilization and the subject of the majority of welding inspection duties is that when heated and cooled at various rates, steel undergoes changes in its atomic structure which can be predetermined, resulting in parts having very desirable mechanical properties with a wide spectrum of usage. The properties can vary from a very high hardness, brittle structure which is ideal for files and cutting tools, to a very ductile, tough structure suitable for bridge beams. These changes occur primarily by controlling the percentage of carbon and other alloying elements, and the metal's heat treatment.

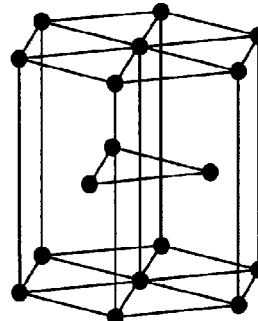
It was noted above that low carbon steel is BCC at room temperature. When heated to a temperature of 1600-1800 degrees F, the BCC structure changes, or 'transforms' to a structure of face centered cubic (FCC) which consists of a cubic structure formed by having one iron atom at each corner of a cube and an atom on each face of the cube. The atoms on each face and corner are shared with adjacent unit cells. The FCC structure for steel is called 'austenite'. The FCC structure can dissolve more carbon than the BCC structure, and as learned earlier, heating a metal also increases its solid solubility limits. Thus, a heated steel can dissolve more carbon in its structure. We can take advantage of this higher solubility for carbon by increasing the dissolved carbon content by heating into the 'austenitizing range', holding for a short period of time, and then quenching rapidly to form the martensitic structure having very high strength. Tempering completes the heat treatment, and we have significantly increased the mechanical strength while maintaining good ductility and toughness. Toughness is defined as the ability of a metal to withstand an impact load without failing in a brittle manner.



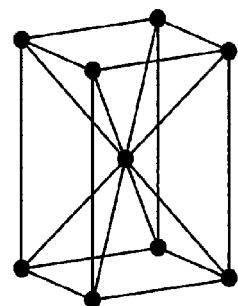
FACE CENTERED CUBIC (FCC)



BODY CENTERED CUBIC (BCC)



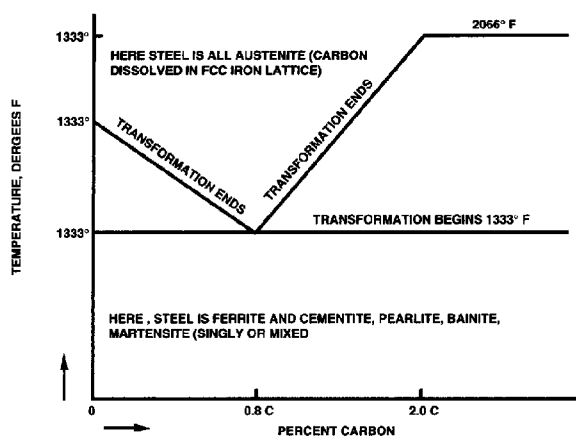
HEXAGONAL CLOSE PACKED (HCP)



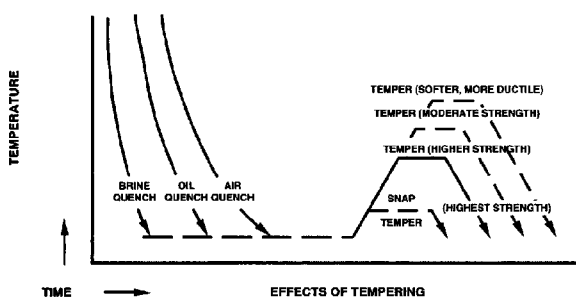
BODY CENTERED TETRAGONAL (BCT)

Common crystalline structures of metals and alloys

6-10



Transformation of steels to Austenite on Heating.



Austenite with Dissolved Carbon

Transformation of the various phases of steel found at room temperature such as ferrite, martensite, pearlite and bainite into austenite is accomplished by heating the metal above its transformation temperature into the austenitizing zone of its phase diagram. The transformation always begins for any steel containing more than a trace amount of carbon at a temperature of 1333 degrees F. In most carbon steel alloys, this transformation occurs over a temperature range from the 1333 degrees F to about 1670 - 2066 degrees F. For a steel containing exactly 0.8% carbon, called a 'eutectoid' composition, the transformation occurs quickly and completely at the 1333 degree F temperature. Transforming the room temperature phases into austenite results in dissolving all the carbon into the austenite structure since the solubility of carbon is much greater due to the increased temperature and the FCC structure being able to dissolve a greater percent of carbon than the BCC structure.

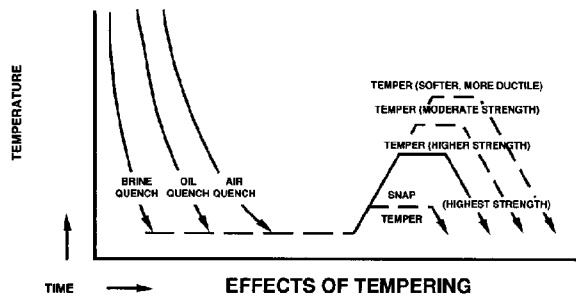
Cooling Rates

On cooling, the transformation reverses; the FCC crystalline structure changes back to BCC. Since the BCC arrangement will not accommodate as much carbon, the excess carbon must form iron carbides (cementite) in one of its several phases. The phase that forms is determined by the speed of cooling. Slow cooling forms ferrite and cementite (pearlite); somewhat faster cooling forms bainite. A very rapid quench forms martensite. The critical cooling rate is governed by the carbon content, and for alloy steels, by their additional chemical composition.

It should be apparent by now why the cooling rate for a specific steel composition determines the need for stress relief heat treatment of a weldment. A cooling rate that forms martensite has moved the iron and carbon atoms into the strained martensitic crystalline structure. Tempering is accomplished by heating the martensite to a temperature between 100 degrees F and 1300 degrees F to soften the steel. At the lower temperatures of tempering, no structural change can be seen on the microscope, but the strength and hardness are reduced, and the ductility and toughness are increased. The changes are more or less proportional to the tempering temperature.

The language of cooling rates and heat treatments is precise. Heating the steel above the transformation temperature to form austenite and cooling it at the slowest rate, as in a furnace cool, is called 'annealing'. Annealing a steel results in placing it in its softest, weakest condition.

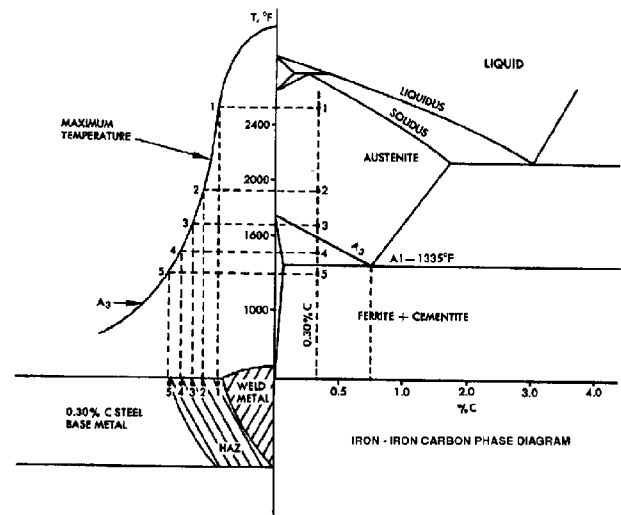
Heating to form austenite, and cooling in 'still air' forms new grains of ferrite and pearlite; this heat treatment is called 'normalizing'. Cooling the steel very rapidly, by quenching in water, oil, or a cold blast of air is called 'quenching'. Quenching the steel results in a martensitic structure, as noted previously. And, as noted earlier, steels quenched to form martensite usually require a 'tempering' heat treatment to lower their



Tempering, as described above, is simply the reheating of the metal, containing martensite, to some appropriate temperature below 1333 degrees F and holding at that temperature for a specified period of time. This permits the as-quenched martensite to change to tempered martensite. The desired compromise between hardness, strength and toughness is obtained by choosing the proper tempering temperature and time cycle. Higher temperatures make the steel softer and weaker, but tougher.

In simple terms, for steels, the faster the cooling rate, the harder and less ductile the resulting structure. While the increased strength is often desirable, the accompanying low ductility will increase the steel's susceptibility to cracking. When welding, the base metal directly adjacent to the molten weld metal will be subjected to the maximum cooling rate because it is heated to a very high temperature and then rapidly quenched due to its contact with the massive, colder base metal. This region, called the heat affected zone (HAZ), will often contain martensite because of the quenching action of the rapid cooling. Consequently, this region is likely to crack unless corrective steps are taken.

One of the more common heat treatments used to reduce the tendency for this high hardness and low ductility in the HAZ is preheat. By preheating the base metal prior to welding to a temperature of 150 - 700 degrees F, the cooling rate will be effectively reduced. This will allow more time for a more ductile microstructure to form rather than martensite, resulting in a more ductile, less crack sensitive weld and HAZ.



Relation between the peak temperatures experienced by various regions in a weld, and how these correlate with the iron-carbon phase diagram.

Another factor having an affect on the cooling rate of the weld zone is heat input or the amount of energy supplied by the welding arc to heat the base metal. As the heat input increases, the cooling rate decreases. Use of smaller diameter welding electrodes, lower welding currents, and faster travel speeds will all tend to decrease the heat input and therefore increase the cooling rate. For arc welding processes, the heat input can be calculated using the formula shown. It is dependent only on the welding current, arc voltage, and travel speed as measured along the longitudinal axis of the weld joint. The heat input formula is:

$$\text{Heat input} = \frac{\text{welding current} \times \text{welding voltage} \times 60}{\text{travel speed}}$$

Heat input is expressed in joules/inch, and travel speed in inches/minute. Joules can also be expressed as watt-seconds. Therefore the number '60' in the numerator simply converts the 'minutes' of the travel speed into 'seconds'.

Other Metallurgical Factors

Fatigue: Any welds which are to be inspected will have to be designed to resist with elastic deformation (temporary) all stresses up to the yield point of the steel, except for weldments subject to fatigue. Welds subject to cyclic stresses must be designed for lower applied stresses to avoid fatigue failures, since metals usually fail by fatigue at stresses below their yield point.

The allowable stresses for bridge welds are defined in special tables that impose higher than normal factors of safety to account for fatigue loading. Safety factors normally are 3 or 4; bridges often have safety factors of 5 or even higher. The design engineer translates these higher factors of safety into larger fillet welds, longer welds, heavier beams, etc., so the bridge will be able to handle the applied cyclic stresses. The welding inspector should be aware of these design differences and inspect accordingly.

Another important factor affecting a metal's resistance to fatigue stresses is its surface configuration. Sharp crevices or notches on the metal's surface result in creating a 'stress riser' which can increase the actual applied load to much higher levels of stress. Typically, engineers have determined that applied stresses can be multiplied by factors from 1 to 10, depending on the nature and shape of the 'notch'. A crack, with its very sharp end conditions, can multiply the applied stress by as much as 10. Undercut can multiply the applied stress by a factor of 3-5, and weld ripples can increase the applied stress by a factor of 2-3.

With the information above, it is easy to see why the surface discontinuities such as undercut, overlap, excess convexity, etc., cause stress risers, or notches, that can significantly reduce the component's fatigue strength. For that reason, fatigue-loaded structures may have their weld surfaces ground to remove surface irregularities. An example of this is found in AWS D1.5, where the allowable depth of undercut for bridges is significantly less than for some other structures.

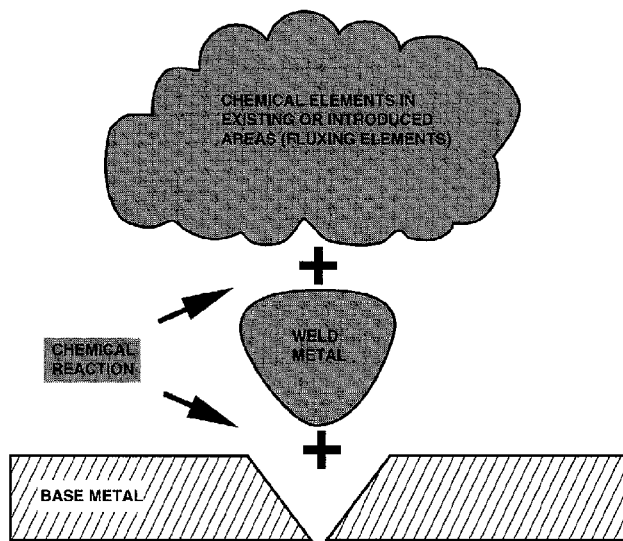
Many fabricated structures are subject to some level of fatigue loading; in fact it is difficult to find a complex structure that has not had some aspect of its design modified to account for fatigue (dynamic) loading.

Internal structure: When alloys are melted in the steel mill, and cast into large ingots, they have a cast structure. These large ingots are formed into the required shapes by a combination of hot working and cold working of the metal. This 'working' changes the internal structure of the metal, but metallurgical discontinuities such as segregation of elements, laminations, seams and laps may remain in the finished product. These discontinuities can become 'planes of weakness' in the finished product. Metals have their highest mechanical properties in the direction of rolling, are somewhat weaker in the direction transverse to the rolling direction, and may often be significantly weaker in their through-thickness direction. The designer and welding engineer must take these factors into account in the design and fabrication of a structure. The inspector should be aware of these conditions which relate to the inspection responsibilities.

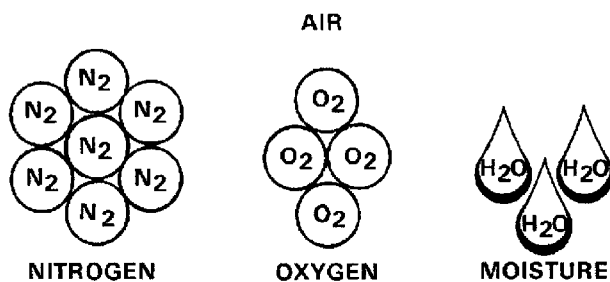
Welding Chemistry

The final aspect of weldability to be discussed is welding chemistry. Welding chemistry deals with the chemical interaction between the base metal elements, the weld metal elements, and the other elements introduced into the area of the weld. The base and weld metals must be compatible; however, other elements in the welding environment must also be considered. For example, the air atmosphere, containing oxygen, nitrogen, and other elements, must be excluded from the weld zone to maintain weld quality. And the elements contained in fluxes must be considered for compatibility as well as any shielding or purge gasses used.

Metals react with their environment to different degrees, depending on the metal and the environment to which it is exposed. We are



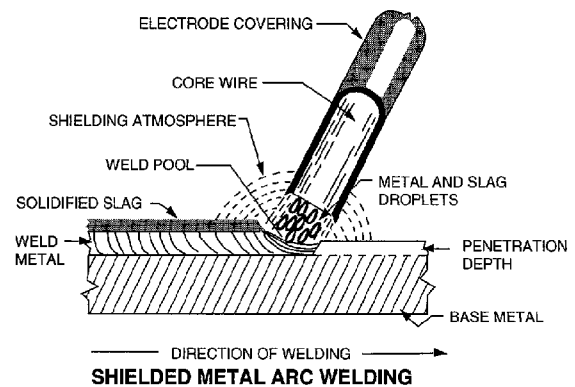
familiar with the 'rusting' of bare steel in moist air; the steel is reacting with the water and the oxygen through a chemical reaction. Many of the stainless steels can also corrode at very high rates if the environment is severe enough. And, as metals corrode, atomic (nascent) hydrogen atoms (H^+) are formed. Earlier discussions about problems with hydrogen emphasize the importance of avoiding corrosion of our welded structures not only because of the wall thinning aspect, but also because of hydrogen formation and diffusion into the steels.



And when molten, metals react with the environments to a much greater degree. Because of this, they must be protected while molten from undesirable elements that may significantly alter their mechanical properties.

Shielding

When welding occurs, the molten weld puddle must be protected from chemical interactions with the unwanted elements. The primary elements causing difficulties are carbon, oxygen, hydrogen, and nitrogen. These unwanted elements are found in moisture, air, improperly adjusted heating flames, and surface contamination. Since the molten metal must be protected, it is accomplished in part through 'shielding', a protective 'blanket of gas' formed from electrode coverings, welding fluxes, shielding gasses, or purge gasses.

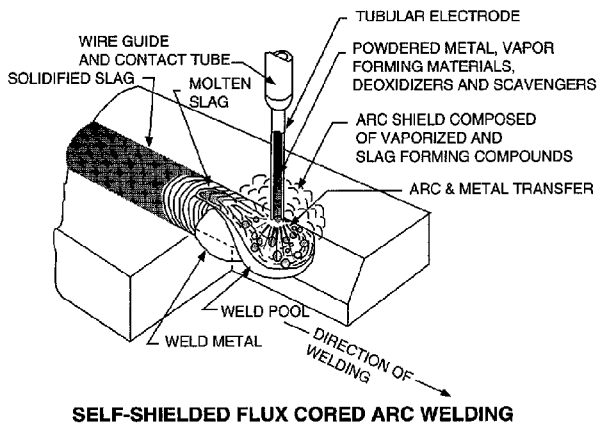


In shielded metal arc welding, the shielding comes from the vaporization of the electrode covering; in gas tungsten arc welding, the shielding comes from the inert gas passing through the torch; in oxyacetylene welding, the shielding comes from the neutral welding flame.

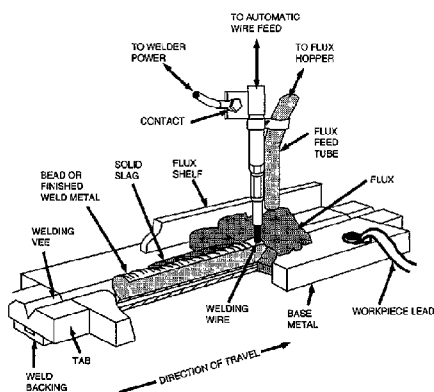
In gas metal arc welding and flux cored arc welding, the shielding gas may be carbon dioxide, CO_2 , or gas mixtures containing carbon dioxide. Since carbon dioxide decomposes on heating into oxygen atoms (O^+) and carbon monoxide (CO), the oxygen can be absorbed into the weld metal. To alleviate this possibility, deoxidizers are added to the electrode compositions to combine with any oxygen present and prevent it from degrading the weld metal properties.

Shielding can also take the form of a blanket of flux, which physically excludes the surrounding atmosphere from the weld zone, and forms a protective slag when heated. Submerged arc

6-14

**SELF-SHIELDED FLUX CORED ARC WELDING**

welding uses a flux covering for shielding and slag formation which protects the weld metal until it cools to room temperature. The protective slag is formed during the heat of welding, and contains deoxidizers added to the flux. Electroslag uses a similar granular flux for shielding.

**SCHEMATIC VIEW OF SUBMERGED ARC WELDING PROCESS**

Weld Metal Composition

The elements composing a weld come from a variety of sources; the base metal adjacent to the weld which is melted, the weld filler metal, fluxes if used, and the shielding agents coming into contact with the weld puddle. Some welds are made without filler metal, and are referred to as 'autogenous' welds. Examples are longitudinal seam welds in tubing, and edge welds and corner welds in sheet metal fabrication. For these welds,

the base metal is formed to permit its being melted and supplying the necessary molten puddle to complete the weld. Some groove welding procedures start with an autogenous root pass, and are completed with filler metals.

The welding inspector must recognize the positive and negative chemical aspects of weld metal composition, and their effects on the finished product. For example, if a weld is made without filler metal, the absence of deoxidizers normally contained in filler metals and fluxing agents may result in the presence of porosity or even cracking.

Hydrogen Contamination

Since hydrogen is present in moisture, oil, and other organic compounds, and always forms during metal corrosion, the inspector must be aware of its formation and possible welding problems. The molten puddle must be protected from hydrogen to avoid cracking or reduction of the mechanical properties of the weld. Cleanliness of the joint is very important, as well as proper storage of fluxes and welding electrodes. Low hydrogen electrodes must be kept in heated storage ovens after opening the original containers. Shielding and purging gasses should be purchased with a - 40 degrees F dewpoint to make sure they don't contain moisture. Some special welding procedures may require these gases having a dewpoint of - 80 degrees F. The lower the dewpoint, the drier the gas.

It must be noted the shielded metal arc electrodes with a cellulosic coating such as EXX10 and EXX11 must not be kept in heated storage. They should be kept dry and stored at room temperature. Heating these electrodes destroys the covering chemistry by removing moisture from the covering which is required for satisfactory performance. These two classes of electrodes are usually limited to welding plain carbon steels, with low to medium carbon content.

Welding Chemistry of Specific Base Metals

The chemistry of the base metals and their corresponding filler metals must be matched for best results. Electrodes have been designed for welding almost every metal. We have noted that as the carbon content increases, the weldability decreases. Thus, plain carbon steel base metals with carbon contents of 0.15% to 0.40% are generally considered easily weldable. As the base metals' carbon content increases above about 0.40%, they become more difficult to weld, and may require changes in the welding procedures such as adding preheat.

Also, as the percentage of other elements added to the base metals increase in percentage, weldability usually goes down. Increased chromium, molybdenum, nickel and other elements may require the use of preheat, interpass temperature control, and post weld heat treatments. Preheating the higher carbon base metals, and those with higher element percents noted above, improves their weldability. This improvement occurs due to several aspects; the weld and HAZ cool more slowly when preheated, the formation of martensite is reduced, hydrogen is removed from the base metal, and the effects of any contamination are minimized.

Carbon Equivalent Calculation

The weldability of carbon steels certainly depends on the base metal's chemistry. A formula has been developed to aid in quantifying its weldability, and determining whether preheat is needed or not. Many such formulas have been developed, but they all take into account the primary alloying elements of the base metal, and determine the effect of each based on a corresponding percent of carbon. The elements usually found in these 'carbon equivalent' (CE) formulas include carbon, manganese, chromium, nickel, copper, silicon, and molybdenum. One such formula is listed, and it determines the effect of each element noted regarding martensite

formation. Most of the elements promote martensite formation, but to lesser degrees than carbon, and their actual percentage is reduced to a 'carbon equivalent' by dividing by some number.

$$CE = \%C + \frac{(\%Mn + \%Si)}{6} + \frac{(\%Cr + \%Mo)}{5} + \frac{(\%Ni + \%Cu)}{15}$$

When the CE computed by this formula exceeds 0.40, it is recommended that the base metal be preheated in the range of 200 - 400 degrees F. If the CE exceeds 0.60, the preheat range should be increased to 400 - 700 degrees F. Additionally, as the CE rises above 0.40, low hydrogen electrodes are helpful, and post welding heat treatments may be required. Since there are many different CE formulas, the welding inspector must get assistance from the welding engineer in their selection to insure their proper usage.

Welding Chemistry of Stainless Steels

The word 'stainless' is a bit of a misnomer when applied to the classes of metals referred to as stainless steels, since it usually means they resist corrosion. However, in severe corrosive environments, many of the stainless steels corrode at very high rates. The stainless steels are defined as having at least 12% chromium. There are many types of stainless steels, and the welding inspector should recognize this when discussing them and use the proper designation for each type.

The four main classes of stainless steels are ferritic, martensitic, austenitic, and precipitation hardening. The first three categories refer to the stable room temperature phase found in each class. The last one, often called 'PH' stainless steels, refers to the method of hardening them by an 'aging' heat treatment, a precipitation hardening mechanism as opposed to the quenching and tempering mechanism. The stable room temperature phase found in stainless steels depends on the chemistry of the steel, and some stainless steels may contain a combination of the different phases. The more common stainless steels are the austenitic grades, which are

identified by the '200' and '300' series grades; 304 and 316 stainless steels are austenitic grades. A 416 steel is a martensitic grade, and 430 is a ferritic grade. One of the common PH stainless steels is a 17-4 PH grade.

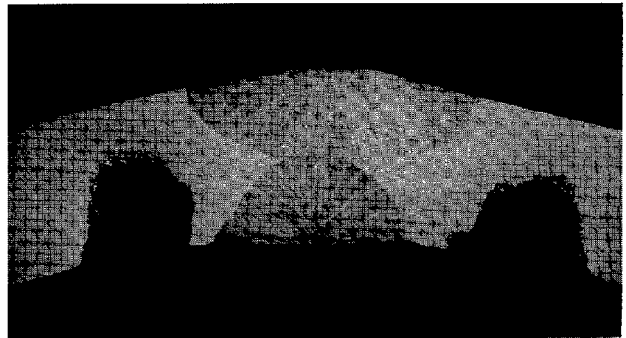
As you might expect, the weldability of these grades varies significantly. The austenitic grades are very weldable with today's available filler metal compositions. These grades can be subject to hot short cracking, which occurs when the metal is very hot. This problem is solved by controlling the composition of the base and filler metals to promote the formation of a 'delta ferrite' phase which helps eliminate the hot short cracking problem. Typically, cracking will be avoided by selecting filler metals with a delta ferrite percent of 4-10%. This percentage is often referred to as the 'Ferrite Number' and can be measured with a magnetic gage. The delta ferrite can be measured using the magnetic gage since delta ferrite is BCC and magnetic, while the primary phase, austenite, is FCC and non-magnetic.

The ferritic steels are also considered weldable with the proper filler metals. The martensitic grades are the most difficult to weld, and often require special preheating and post weld heat treatment. Procedures have been developed to weld these materials, and must be followed carefully to avoid cracking problems and maintain the mechanical properties of the base metals. The PH stainless steels are also weldable, but attention must be given to the changes in mechanical properties caused by welding.

One of the common problems found when welding the austenitic grades is referred to as 'carbide precipitation', or 'sensitization'. When heated to the welding temperatures, a portion of the base metal reaches temperatures in the 800 - 1600 degree F range, and within this temperature range, the chromium and carbon present in the metal combine to form chromium carbides. The most severe temperature for their formation is about 1250 degrees F, and this temperature is passed through twice on each welding operation

cycle; once on heating to weld and again on cooling to room temperature.

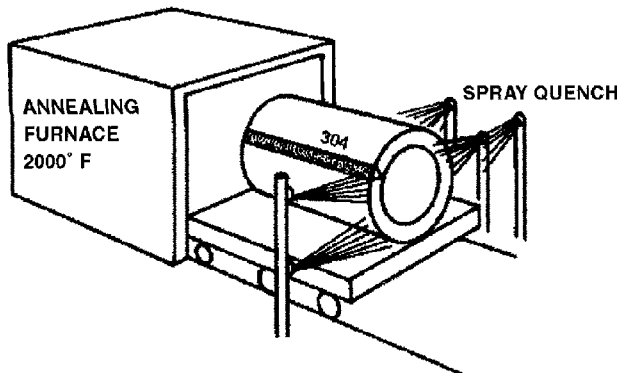
These chromium carbides typically are found along the grain boundaries of the structure. The result of their formation is the reduction of the chromium content within the grain itself adjacent to the grain boundary, called 'chromium depletion', resulting in reducing the chromium content below that desired. The final result of this chromium depletion of the grain is a reduced corrosion resistance of the grain itself due to its reduced chromium content. In certain corrosion environments, the edges of the grains corrode at a high rate, and is called 'intergranular corrosion attack', or IGA.



Corrosion by intergranular attack (IGA) caused by sensitization of the HAZ.

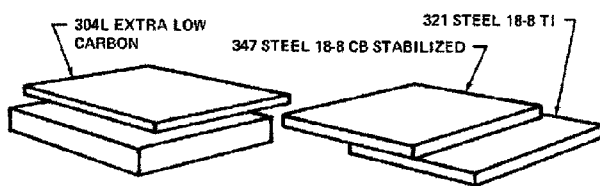
Sensitization of austenitic stainless steels during welding can be attacked by several methods. The first method involves re-heat treating the completed structure by heating to 1950 degrees F and quenching rapidly in water. This reheating breaks up the chromium carbides permitting the carbon to be redissolved into the structure. However, this heat treatment can cause severe distortion of welded structures.

A second method is the addition of stabilizers to the base and filler metals. The two most common examples of stabilization are the addition of titanium or columbium (niobium) to the 300 series alloys in amounts equal to 8 or 10 times the



For Stabilization Heat Treatment use 1500° F, no quench needed.

carbon content. These alloying stabilizers preferentially combine with the carbon and reduce the amount of carbon available for chromium carbide formation, maintaining the alloys' chromium content and corrosion resistance. When titanium is added, we have the austenitic stainless alloy 321; when columbium is added, we have the 347 grade.



Prevention of corrosion in welded stainless steel.

The third method is the reduction of the carbon content in the base and filler metals. Initially, these low carbon austenitic stainless steels were referred to as 'Extra Low Carbon', or ELC for abbreviation. Today, they are referred to by the letter "L" meaning the carbon content is less than 0.03%. (The standard grades contain up to 0.08% carbon.) By reducing the carbon content in the alloy, less carbon is available to combine with the chromium, and sensitization is reduced during welding. These low carbon grades do have slightly reduced mechanical properties because of their lower carbon content, and this must be considered when selecting these alloys, especially for high temperature use.

Welding Chemistry of Aluminum Alloys

Aluminum alloys have a very tenacious oxide film on their surfaces which forms very rapidly when the bare aluminum is exposed to air, and these oxide films give protection in corrosive environments. These same oxides on the surface do interfere with the joining processes, however. To braze or solder these alloys, fluxes are used to break down the oxide film so the parts can be joined. When welding, alternating current is used which results in breaking down of the oxides by the current reversal of AC welding, and re-formation of the oxide film is avoided by shielding with helium or argon gas. The AC welding method is sometimes referred to as a 'surface cleansing technique'.

The metallurgy of aluminum and its alloys is very complex, especially regarding the great number of alloy types and heat treatments. The proper filler metals for most every grade and heat treat condition can be found in ANSI/AWS A5.10, *Specification for Bare Aluminum and Aluminum Alloy Welding Electrodes and Rods*.

Welding Chemistry of Copper Alloys

Pure copper and many of its alloys cannot be hardened by a quench and temper heat treatment as steel can. These alloys are usually hardened and made stronger by the amount of 'cold work' introduced when forming them into the various shapes. The act of welding softens the cold worked material and must be considered before welding on work-hardened copper alloys. There is a series of copper alloys that are strengthened by 'aging', a treatment similar to the precipitation hardening used on the PH stainless steels. When welding on these alloys, a postweld heat treatment is usually specified to restore the original mechanical properties.

One of the major problems found on welding copper and its alloys is due to their relative low melting point and very high thermal conductivity. Considerable heat must be applied to the metal to overcome its loss through conductivity, and the

relatively low melting point often results in the metal melting earlier than expected and flowing out of the weld joint. Most copper alloys are weldable with proper technique and practice.

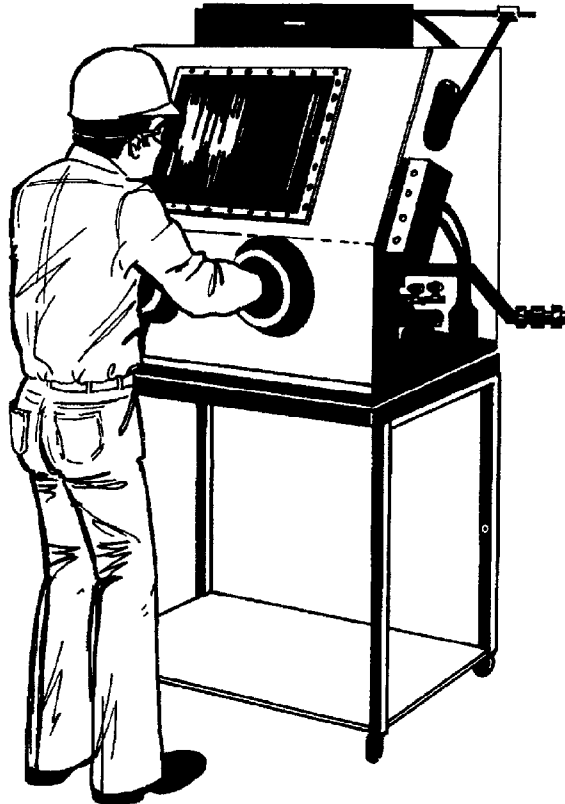
Welding Chemistry of the Reactive Metals

There are three metals grouped into the class of 'Reactive Metals'. These are titanium, zirconium and tantalum. These metals are so named because they are extremely reactive with other elements, especially when heated to the temperature required to weld. When they react with even traces of other elements, such as oxygen, hydrogen, and nitrogen, they become very embrittled and hard. Extra precaution is required in shielding and purging, and often, tantalum and zirconium are required to be welded in a purging chamber. For titanium, a full shielding technique, or a trailing shield may be sufficient.

It has been stated that because of the great affinity these alloys have for trace contaminants, the 'art of welding' is really the art of proper cleaning and purging. When attention is given to these two aspects, cleaning and purging, high quality welds can be made.

Summary

While the welding inspector is not responsible for selecting the base metals and filler metals, the inspection responsibility will involve many decisions which have a basis on metallurgical principles. This information has been covered to provide the inspector with a background and basic understanding of many of the principles involved. The inspector will benefit from the additional knowledge of the metallurgical considerations applied to the fabrication of structures that explain the behavior of metals during welding.



Welding in a Controlled Atmosphere

REVIEW -**CHAPTER 6
WELDABILITY, WELDING CHEMISTRY
AND
WELDING METALLURGY**

- Q6-1** As a metal is heated:
- a. energy is added to the structure.
 - b. the atoms move farther apart.
 - c. the atoms vibrate more vigorously.
 - d. the metal expands.
 - e. all of the above
- Q6-2** The state of matter which exhibits the least amount of energy is:
- a. solid
 - b. liquid
 - c. gas
 - d. quasi-liquid
 - e. none of the above
- Q6-3** A problem occurring in weldments caused by the nonuniform heating produced by the welding operation is:
- a. porosity
 - b. incomplete fusion
 - c. distortion
 - d. slag inclusions
 - e. none of the above
- Q6-4** All but which of the following will result in the elimination or reduction of residual stresses?
- a. vibratory stress relief
 - b. external restraint
 - c. thermal stress relief
 - d. peening
 - e. postweld heat treatment

6-20

- Q6-5** Steel exists in which of the following crystal arrangements?
- a. HCP
 - b. FCC
 - c. BCC
 - d. a and b above
 - e. b and c above
- Q6-6** Rapid cooling of a steel from the austenitic range results in a hard, brittle structure known as:
- a. pearlite
 - b. carbide
 - c. cementite
 - d. bainite
 - e. martensite
- Q6-7** Very slow cooling of steel may result in the production of a soft, ductile micro structure which has a lamellar appearance when viewed under high magnification. This structure is referred to as:
- a. martensite
 - b. pearlite
 - c. bainite
 - d. ferrite
 - e. cementite
- Q6-8** When rapid cooling produces a martensitic structure, what non-austenitizing heat treatment may be applied to improve the ductility of the steel?
- a. quenching
 - b. tempering
 - c. annealing
 - d. normalizing
 - e. none of the above
- Q6-9** The use of preheat will tend to:
- a. result in a wider heat affected zone
 - b. produce a lower heat affected zone hardness
 - c. slow down the cooling rate
 - d. reduce the tendency of producing martensite in the heat affected zone
 - e. all of the above

- Q6-10** Which of the following changes will warrant the addition or increase in the required preheat?
- a. decreased carbon equivalent
 - b. increased carbon equivalent
 - c. increased base metal thickness
 - d. a and c above
 - e. b and c above
- Q6-11** What heat treatment is characterized by holding the part at the austenitizing temperature for some time and then slow cooling in the furnace?
- a. normalizing
 - b. quenching
 - c. annealing
 - d. tempering
 - e. stress relief
- Q6-12** What heat treatment is characterized by holding the part at the austenitizing temperature for some time and then slow cooling in still air?
- a. normalizing
 - b. quenching
 - c. annealing
 - d. tempering
 - e. stress relief
- Q6-13** Increasing the heat input:
- a. decreases the cooling rate and increases the likelihood of cracking problems.
 - b. decreases the cooling rate and decreases the likelihood of cracking problems.
 - c. increases the cooling rate and increases the likelihood of cracking problems.
 - d. increases the cooling rate and decreases the likelihood of cracking problems.
 - e. none of the above
- Q6-14** Increasing preheat:
- a. decreases the cooling rate and increases the likelihood of cracking problems.
 - b. decreases the cooling rate and decreases the likelihood of cracking problems.
 - c. increases the cooling rate and increases the likelihood of cracking problems.
 - d. increases the cooling rate and decreases the likelihood of cracking problems.
 - e. none of the above

6-22

Q6-15 Increasing the carbon content:

- a. decreases the likelihood of cracking problems.
- b. increases the likelihood of cracking problems.
- c. has nothing to do with the likelihood of cracking problems.
- d. all of the above
- e. none of the above

Q6-16 Which of the following generally follows quenching?

- a. annealing
- b. normalizing
- c. quenching
- d. tempering
- e. stress relief

Q6-17 Which of the following can be accomplished using either thermal or mechanical techniques?

- a. annealing
- b. normalizing
- c. quenching
- d. tempering
- e. stress relief

Q6-18 Which of the following results in the softest structure for steel?

- a. annealing
- b. normalizing
- c. quenching
- d. tempering
- e. stress relief

Q6-19 For a steel having the following composition: 0.11 carbon, 0.65 manganese, 0.13 chromium, 0.19 nickel, 0.005 copper, and 0.07 molybdenum, what is its carbon equivalent using the following formula?

$$CE = \%C + \frac{(\%Mn)}{6} + \frac{(\%Ni)}{15} + \frac{(\%Cr)}{5} + \frac{(\%Cu)}{14} + \frac{(\%Mo)}{4}$$

- a. 0.15
- b. 0.23
- c. 0.28
- d. 0.31
- e. 0.42

Q6-20 For a steel having the following composition: 0.16 carbon, 0.85 manganese, 0.25 chromium, 0.09 nickel, 0.055 copper, and 0.41 molybdenum, what is its carbon equivalent using the following formula?

$$CE = \%C + \frac{(\%Mn)}{6} + \frac{(\%Ni)}{15} + \frac{(\%Cr)}{5} + \frac{(\%Cu)}{13} + \frac{(\%Mo)}{4}$$

- a. 0.23
- b. 0.31
- c. 0.34
- d. 0.41
- e. 0.46

Questions **Q6-21** through **Q6-24** refer to the Heat Input formula below:

$$\text{Heat Input (J/in)} = \frac{\text{Amperage} \times \text{Voltage} \times 60}{\text{Travel Speed (in/min.)}}$$

Q6-21 The FCAW process is being utilized to weld a 1 inch thick structural steel member to a building column. The welding is being done with a 3/32 inch diameter self-shielded electrode with a 150° minimum preheat and interpass temperature. The welding parameters are adjusted to 30 volts, 250 amperes and 12 in/min. What is the heat input?

- a. 375 J/in
- b. 37,500 J/in
- c. 375 kJ/m
- d. a and b above
- e. b and c above

Q6-22 GMAW (short circuiting) welds are produced at 18 volts, 100 amperes and 22in/min. What is the heat input?

- a. 238 J/in
- b. 7333 J/in
- c. 4900 J/in
- d. 30 J/in
- e. none of the above

6-24

- Q6-23** The GMAW process is mechanized for welding 1/8" thick stainless steel sheets against a copper backing bar. The process is operated at 300 amperes, 28 volts and 15 in/min. What is the resulting heat input?
- a. 650 kJ/in
 - b. 650,000 J/in
 - c. 165,000 J/in
 - d. 16,500 J/in
 - e. none of the above
- Q6-24** The GTAW process is being used for welding 1/16" thick titanium using DCEN at 110 amperes, 15 volts and 6 in/min. What is the heat input?
- a. 21 000 J/in
 - b. 21 kJ/in
 - c. 16,500 J/in
 - d. a and b above
 - e. b and c above