THE METALLURGICAL EFFECTS OF WELD SEAM HEAT TREATING

By Robert K. Nichols, PE

High Frequency Welding has been successfully applied to many common and a few exotic metals but by far the greatest tonnage of material produced is made of carbon steel. The simple reason for this is that steel exhibits a wide variety of mechanical properties that can be developed by common industrial processes.

WHAT IS STEEL?

Steel is an alloy (mixture) of iron with less than about 1.8% carbon in addition to various other elements such as manganese, silicon, chromium, nickel, molybdenum, etc. Most steel used for tubulars has a carbon content of between .05 and .25 per cent carbon. The terms "low carbon steel" and "mild steel" refer to steel with a carbon content between .05% and .20%. Alloying elements are usually added to promote a specific attribute such as hardness or corrosion resistance. Some elements, such as sulfur and phosphorus, are impurities and are generally reduced in the steel making process to some practical minimum.

TYPICAL CARBON STEEL CHEMISTRY

- **Carbon: .08% to .25%**
- **Manganese: .20% TO 1.00%**
- **Silicon: .15% to .35%**
- **Phosphorus: .04% maximum**
- **Sulfur: .03% maximum**
- **Aluminum: .03% to .06%**

Fig 1.

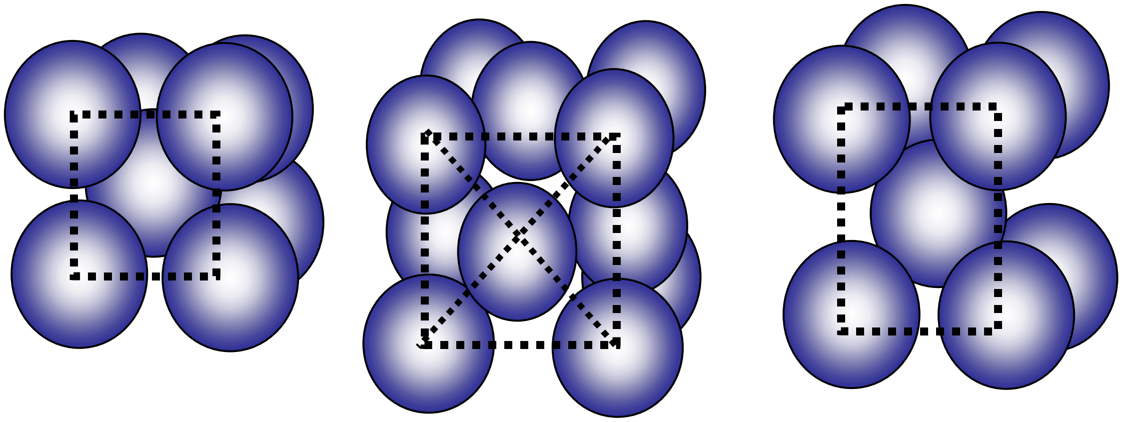
WHAT CONTROLS THE STRENGTH OF STEEL?

The strength of steel is influenced by its microstructure (the type of crystal patterns). The microstructure is controlled by the arrangement of the atoms of the various elements in the steel. Heating and cooling of the steel influences this atomic arrangement. There are three basic crystal shapes commonly seen in carbon steel (see Fig. 2)

Figure 2 shows that all three of the crystal shapes are types of cubes. The body centered cubic (BCC) has an atom at each corner and one right in the center of the cube. The face centered cubic (FCC) also has an atom at each corner and one on each face of the cube. The body centered tetragonal (BCT) is basically the same as the body centered cubic except that one axis is longer than the other two.

The BCC crystal is also known as ferrite (from the Latin word for iron, ferrum). The FCC crystal is also known as austenite (named after Sir William Roberts-Austen). The BCT crystal is also known as martensite (named after Adolf Martens).

At room temperature, iron exists as ferrite. When the iron is heated to about 1330 °F (721° C), it begins to change to the face centered cubic form, austenite. The change is not instantaneous but takes place over a range of temperatures depending on the carbon content. The ferrite is completely transformed to austenite at about 1,560 °F (850 °C) for a .10% carbon steel.



Body Centered Cubic (Ferrite)

Face Centered Cubic (Austenite)

Body Centered Tetragonal (Martensite)

Fig 2. Iron crystal forms at various temperatures

WHERE IS THE CARBON IN THE STEEL?

Carbon atoms are much smaller than iron atoms and can actually fit between iron atoms. Fig 3 illustrates how this is possible. It can be seen that the iron atoms are closer together when the iron exists as ferrite than when it is austenite. Since the iron atoms allow more room as austenite, it should come as no surprise that more carbon could be dissolved in austenite than in ferrite.

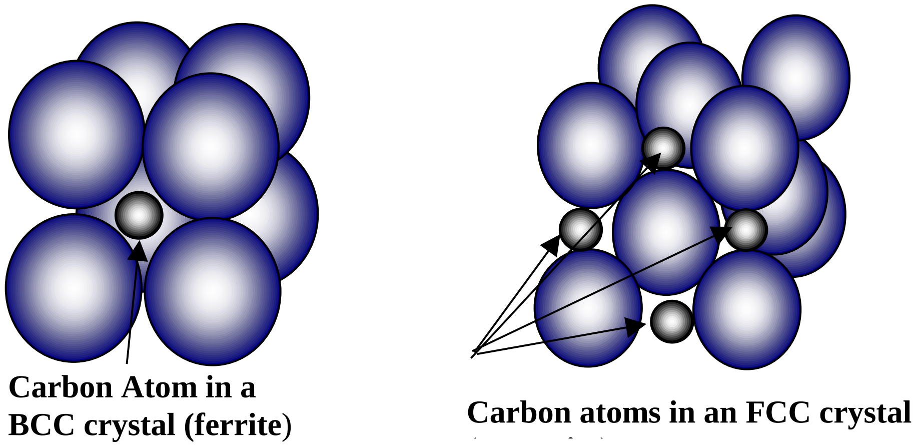


Fig 3. Carbon in Iron crystals

In fact, at room temperature, virtually no carbon can be dissolved in ferrite. Any carbon in the steel exists as a carbide, that is, a chemical substance where the carbon atom is bonded to several iron atoms. The carbides in the ferrite are much like stones in a cement matrix. The carbides are very hard and the more carbon there is in the steel, the harder and stronger the steel will be.

If ferrite has been heated to a temperature sufficient to completely transform it to austenite, the carbides begin to dissolve and the carbon moves to the spaces between the iron atoms.

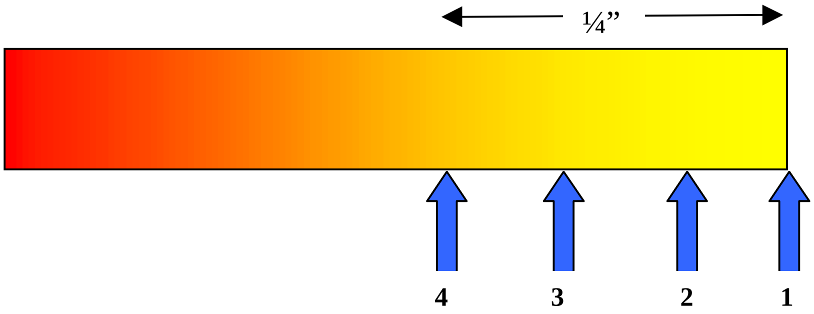
This is the most stable condition for carbon in austenite. However, when the austenite is cooled, the carbon must escape from the spaces between atoms as the austenite transforms back into ferrite.

If cooling is slow enough for the carbon atoms to recombine with the iron atoms, carbides are formed again and the structure is much like it was before heating. If the cooling rate is significantly accelerated, the austenite undergoes a transformation to the third type of crystal discussed previously: martensite. Martensite is called a metastable phase because iron really doesn’t want to exist as a body centered tetragonal crystal. The carbon is still trapped between the iron atoms and the crystal lattice is under great strain. This means that the iron is very hard and brittle. The best way to relieve the strain is to reheat the steel to a temperature below that which will cause the formation of austenite. This process is called tempering. It allows the carbon atoms to escape from the iron crystal lattice and recombine to form carbides. This reduces the hardness and improves ductility.

Tempering and time are inversely related. This simply means that you can accomplish in a short time at high temperature what you accomplish in a long time at a low temperature.

THE HIGH FREQUENCY WELD

The HF weld relies on rapidly heating the edges of the strip to form a forge weld. The resistance of the steel to the flow of electricity causes the edges of the strip to get very hot. Unique to HF welding, the current flows only on the edges of the strip so that heating is very localized. However, within the heated zone, many of the metallurgical processes just discussed are taking place. Figure 4 represents the edge of the strip being heated for an HF weld.



1. **Liquid, no crystal structure.**
2. **1,850° F (1,000° C): Face Center Cubic Austenite**
3. **1,200° F (650°C): FCC Austenite and BCC Ferrite**
4. **450° F (230° C): BCC Ferrite and carbides**

Fig 4. Heat distribution on edge of strip.

METALLURGICAL CHANGES IN THE WELD AREA

When the edges of the strip are heated to 1330° F (720° C), the iron begins to transform from ferrite to austenite. The carbides begin to dissolve and move into the spaces between the iron atoms of the austenite. The carbon continues to move (diffuse) toward the hottest part of the edge because that is where it is most soluble. The heat flows inward from the edges, raising the temperature of the iron, causing the changes in crystal shapes to take place. As the edges melt, the iron atoms are no longer bound to one another to form regular crystal shapes. The atomic arrangement is totally random.

As the carbon in the steel moves to the molten edges, it is exposed to oxygen. The carbon and the oxygen bond together to form CO and CO_2. As the carbon is oxidized from the steel, only the iron remains and it will exist as either ferrite or martensite when the edges cool.

When the edges of the strip are forced together by the weld rolls, the molten iron is forced out of the joint along with the scale that has formed on the surface. The liquid iron and the iron oxide scale have prevented the oxygen from combining with the iron deeper into the edges and when the two edges are forced together they metallurgically bond. This bond is almost as strong as the parent material. It is only “almost as strong” because of the ferrite bond line, which is the result of the oxidation of the carbon from the steel. No carbon remains to add strength to this bond line. Fortunately, in the process of making the forge weld, the wall thickness in the weld area is increased and this generally compensates for the slightly weaker bond line. See Fig 5.

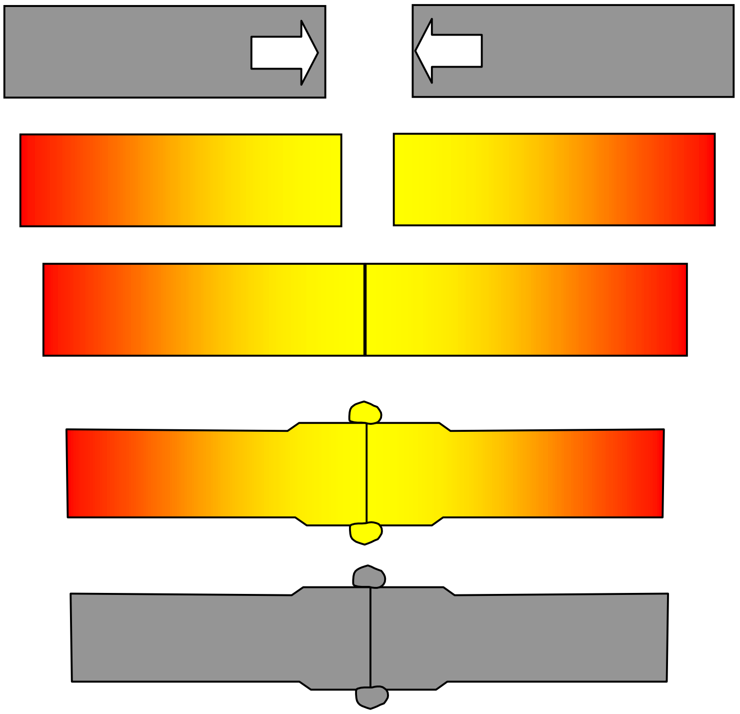


Fig 5. Schematic sequence of HF forge weld

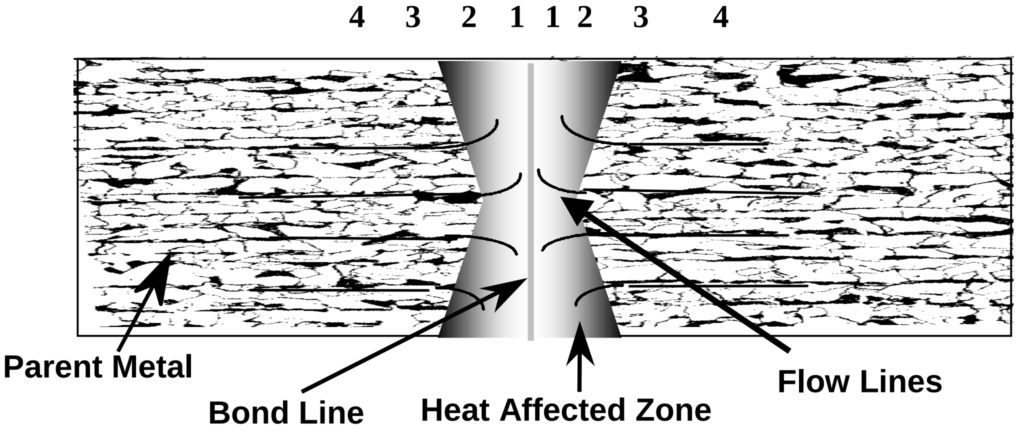


Fig. 6. Schematic of Normal HF weld. Numbers correspond to those in Fig. 4

Figure 6 represents a normal High Frequency weld area. The numbers over the weld roughly correspond to those in Fig. 4. After the weld is complete, there is a series of microstructures surrounding the weld bond line. First, there is the parent metal in position 4. It has been unaffected by the heat. At position 3 is the edge of the Heat Affected Zone (HAZ) marking the boundary between parent metal and metal that has been changed by the heat. At position 2 is the HAZ. this is metal that has been heated but not melted. At position 1 is the bond line and it represents the highest temperature achieved by any metal not squeezed out of the weld.

The HAZ represents the area that is most likely to present problems when welding steels with a carbon content greater than .10%.

Examination of Fig 7 shows that the parent metal is a mixture of white ferrite grains and darker streaks. These dark streaks are ferrite with carbides precipitated in it. Metallographically, it is known as pearlite. It is the carbon in the pearlite which, when the HAZ is hot, dissolves into the austenite. As the HAZ cools after the weld is complete, it can transform back to ferrite with carbides in it or, if cooling is fast enough, to martensite. It is the pearlite bands that are most likely to transform to martensite but a large percentage of the HAZ may also become martensitic (See Fig 6).

Rapid cooling can take place even if there is no water applied to the weld area while it is hot. The cold mass of metal represented by the walls of the tube on either side of the weld is a great heat sink and can chill the weld area sufficiently to form martensite. Obviously, thin walls will cool faster than thick walls.

The hard, brittle martensite in the HAZ often causes failures in flattening and flaring tests and can precipitate catastrophic failures in service. It is for this reason that the API (American Petroleum Institute) and ASTM (American Society for Testing and Materials) both specify that on certain grades of pipe, the weld seam must be processed in such a manner that no untempered martensite remains.

To remove the unwanted martensite, the weld seam must be reheated by seam normalizing or seam tempering.

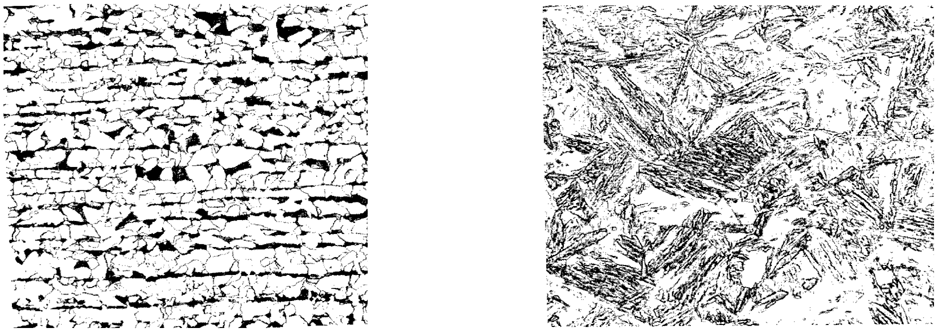


Fig 6. Pearlite/Ferrite (100x) **Martensite (400x)**

WELD SEAM HEATING EQUIPMENT

Weld seam heating equipment is related to induction welding equipment in that it utilizes an inverter to supply power to an inductor. The inductor is a water-cooled copper tube, 3/8” x 3 ft (9.5mm x 914mm). When power is applied to the tube, an intense magnetic field is developed around it. To focus the magnetic field and improve the efficiency of the system, horseshoe shaped silicon steel wafers are stacked over the tube (See Fig 7). The inductor is designed to ride approximately .250” (6mm) above the weld seam. Increasing this gap results in a dramatic loss of power since the strength of the magnetic field, and thus the power, diminishes as the square of the distance between the inductor and the tube. For example, increasing the gap from .25” to .5” will drop the power available by 75%.

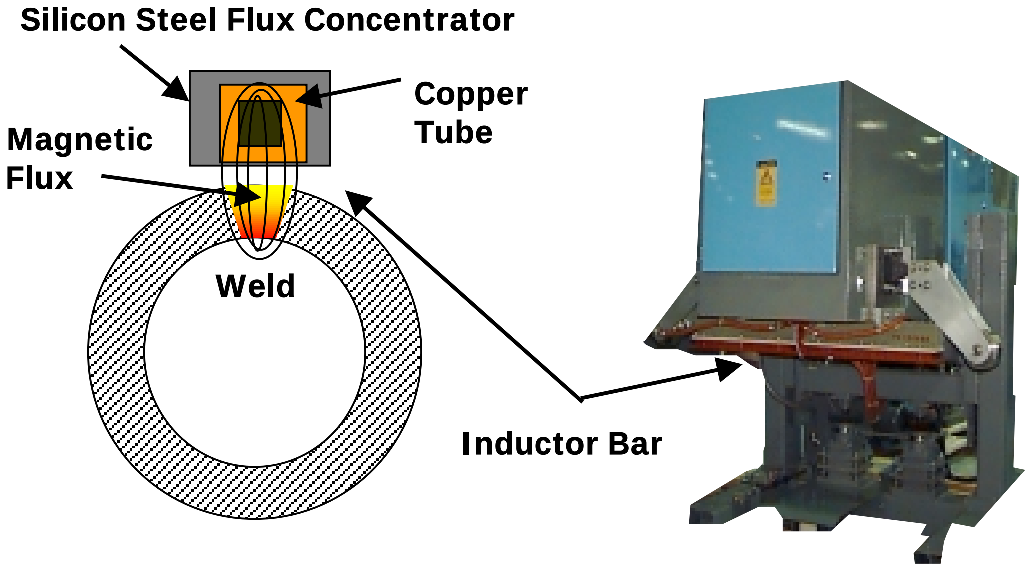


Fig 7. 500 kW x 3 kHz Seam Normalizer

SEAM NORMALIZING

Seam normalizing heats the entire HAZ back into the austenitic temperature range, usually around 1750° F (944 °C). This allows the martensite to transform back into austenite. Care must be taken that the temperature does not exceed 1850° F (1010° C) or the grains of metal in the weld area will begin to coarsen creating a zone of weakness and potential for accelerated corrosion. *For the process to be fully effective, the weld seam must be allowed to cool in air to below 1300° F (700° C), thus avoiding the re-forming of martensite.* While no metallurgical changes will occur if water is applied to the weld area after it has cooled below 1300° F (700° C), cracking and warping are possible. For this reason that it is recommended that the weld area be cooled to less than 700° F (370° C) before water-cooling is applied. A rule of thumb is to allow 2 feet (.6 meters) for each foot per minute (.3 meters per minute) of mill speed. For example, if your mill runs at 100 feet per minute (30 meters per minute) you should plan on providing 200 feet (60 meters) of air cooling before applying water to the weld seam. Retrofitting a mill with a seam normalizer may require significant relocation of down-stream equipment.

SEAM TEMPERING

Seam tempering is almost the same as seam normalizing except that it heats the HAZ to a temperature lower than what is required to re-austenitize the steel. This temperature is usually between 1000° F (540° C) and 1300° F (700° C). When the HAZ is tempered, the hardness is reduced and ductility is increased. However, the HAZ now contains tempered martensite and this may represent what is called a galvanic cell.

A galvanic cell can be created when two different microstructures exist in close proximity on the same piece of metal. It is a natural phenomenon that, in the presence of an electrolyte, can cause accelerated corrosion of the weld area. In many applications, this represents no significant hazard. In critical applications where corrosion of the weld line could lead to catastrophic failure, seam tempering may not be sufficient.

One advantage of seam tempering is that because the weld seam is heated to a lower temperature, it does not take as long to cool down and air-cooling distances can be shorter.

SEAM QUENCH AND TEMPERING

There is some interest, particularly among producers of large diameter, heavy walled pipe, in a third process called quench and tempering. More accurately, it is austenitize, quench and temper. In this process one inductor heats the weld seam to approximately the same temperatures as used in seam normalizing. The weld area is then sprayed with water to rapidly quench the hot seam and form a fully martensitic structure. A second inductor then tempers the seam as described above. The main benefit of this process is that it requires less cooling time from the tempering temperature and may more easily be retrofitted onto an existing mill. However, any improvements in weld seam strength and toughness can be compromised by a quench crack or accelerated corrosion. Additionally, the process requires considerably more attention to process control and testing of the results.

SUMMARY

Iron will change crystal structures when heated, often resulting in unacceptable hardness in the weld area. To prevent this, control welding temperatures and cooling rates after welding. When necessary, seam heat-treating can restore parent material properties. Carefully control seam heat treating temperatures and allow sufficient time for the weld seam to cool before applying water.

The Metallurgical Effects of Weld Seam Heat Treating

By
Robert K. Nichols, PE
Manager-Applications and
Process Engineering
Thermatool Corp.

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