Seam Annealing of HF Welded API Pipe

Dr. Paul Scott
Vice President, Technology
Thermatool Corp
East Haven, CT, USA

Why Seam Anneal?

Seam annealing is an important in-line process for making high frequency (HF) welded pipe to API 5L or 5CT specifications. Its purpose is to produce pipe compliant with the following API requirements:

- **From API 5L, Section 5.1.3.3.1 Electric Welded Pipe:** For grades higher than X42, the weld seam and the entire heat affected zone shall be heat treated so as to simulate a normalizing heat treatment…

  Also:

  For grades X42 and lower, the weld seam shall be similarly heat treated, or the pipe shall be processed in such a manner that no untempered martensite remains.

- **From API 5 CT, Section 6.2.1 Heat Treating – General:** The weld seam of electric-welded pipe shall be heat-treated after welding to a minimum temperature of 540°C (1000°F) or processed in such a manner that no untempered martensite remains.

Induction seam annealing is the most widely used method for either normalizing the seam of HF welded pipe or removing its untempered martensitic structure.

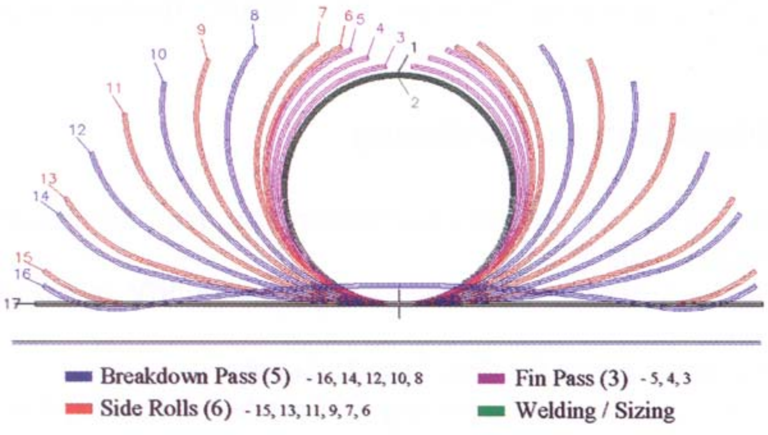
The HF Pipe Making Process and a Little Metallurgy:

HF welded pipe is fabricated by forming strip steel into a tubular shape using a roll forming mill and then welding the edges together. This process is illustrated in Figure 1. The welding is done by using either electrical contacts or an induction coil to create a high frequency electric current (generally between 100 kHz and 400 kHz) along the strip edges. Because of the nature of high frequency electrical currents, a physical phenomenon called the “Proximity Effect” forces most of the current to flow on the strip’s edges. This causes the edges to heat to the forge welding temperature and a set of “squeeze” rolls force the edges together under sufficient pressure to produce a forge weld. The weld is then allowed to cool at a relatively high rate to insure that it has good integrity. The result is, that while the weld is a forge weld with no “cast” structure, the metallurgical properties in the Heat Affected Zone (HAZ) are now different than those of the rest of the pipe.

Figure 1

The HF Pipe Making Process

a. Typical roll forming type tube mill used to produce API pipe



b. "Flower Pattern" Diagram showing how the forming rolls successively shape the strip into a pipe.

c. HF Weld Area showing the induction work coil and the weld forging roll box

Let’s look in greater detail at the transformation that occurs in the weld zone. Seam welded API product is made from various high tensile steels that have a carbon content between about 0.05% and 0.26% for 5L products and between about 0.1% and 0.5% for 5CT products. When these steels are heated to the forge welding temperature, they achieve a maximum of about 1500 Degrees C (2750 F) although most of the metal at this temperature is squeezed out from the weld zone during the forging process. From this maximum, the temperature decreases as one moves circumferentially away from the weld bond plane. Beginning at the temperature of 721 degrees C (1330 F) to a temperature of about 850 degrees C (1560 F), the iron’s crystalline lattice in the steel undergoes a radical transformation from having a body centered or Ferrite crystalline structure to having a face centered or Austenite crystalline structure. This is illustrated in Figure 2. When this happens, the carbon atoms from the dissolved carbides, which are much smaller than the iron atoms, move into the Austenitic structure to fill the “gaps” between the iron atoms. If the steel is cooled fast enough, as it is after it is forge welded, the iron crystalline lattice undergoes the reverse transformation from the Austenite structure to the Ferrite structure faster than the carbon atoms can escape from their positions between the iron atoms in the crystalline lattice. Hence, they become trapped in the iron lattice. This results in a body centered tetragonal crystalline structure called Martensite. With Martensite, the carbon atoms trapped between the iron atoms put the crystal lattice under great strain. Thus the steel in this region is hard and brittle. This is an undesirable condition and hence the API requirements to eliminate the untempered Martensite. Samples of a weld seam before and after normalizing are shown in Figure 3.

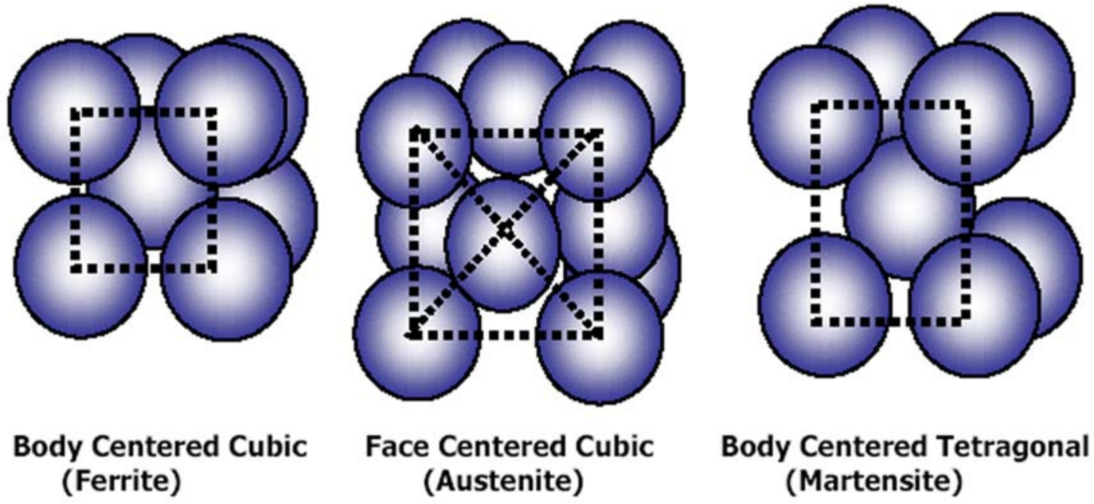
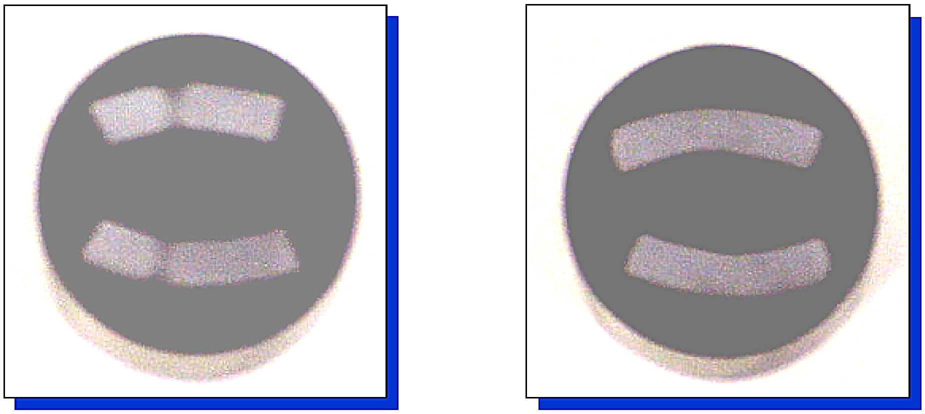


Fig 2. Iron crystal forms at various temperatures



Weld seam before normalizing – Change in metallurgical structure is quite visible

Weld seam after normalizing – No visible change in metallurgical structure.

Figure 3 – Weld Seam Before and After Seam Normalizing

The Metallurgical Effects of "Seam Annealing"

While the process is called "seam annealing", this is a misnomer. It is really a normalizing or tempering type metallurgical process. To achieve the API specifications, the carbon atoms must be freed from the iron's crystalline lattice. To do this, the weld zone must be reheated and then cooled slowly enough so that the carbon atoms can escape.

Tempering is a time versus temperature process. The hotter the temperature of the steel, the faster the carbon atoms will escape from the lattice. Tempering occurs at temperatures lower than the transition temperature between Ferrite and Austenite and in practice is performed between 540 degrees C (1000 F) and 700 degrees C (1300 F).

To normalize the weld seam, the steel is treated to a temperature that retransforms it to Austenite (See Figure 4). It is then allowed to cool very slowly so that it fully returns to a Ferrite and carbine composition. In practice, this means heating the weld seam to between 950 degrees C (1750 F) and 1010 degrees C (1850 F). It is important to note, however, that exceeding 1010 degrees C (1850 F), and certainly 1100 degrees C (2000 F), causes coarsening of the grains of metal in the weld area (grain growth) creating a zone of weakness and potential for accelerated corrosion.

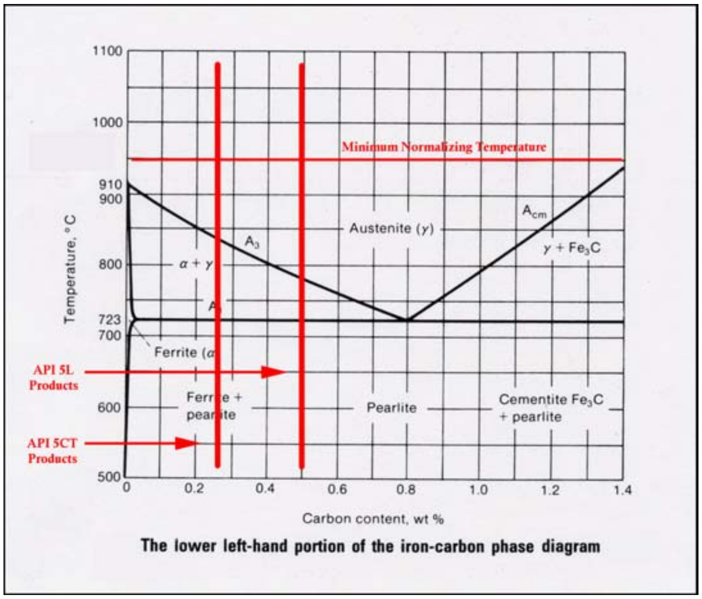


Figure 4 – Steel Phase Diagram and a Function of Carbon Content

Finally, the trend in line pipe materials is toward higher yield steels (80 to 100 kpsi) and many of these are very low carbon, micro-alloyed, thermo mechanically processed (TMP) steels. In this process, the steel slabs are finish rolled at temperatures just above the Austenite formation temperature and then rapidly cooled on a laminar flow table. Rolling at this relatively low temperature crushes the Austenite the result is a very fine-grained Ferrite. The weld seam for these materials cannot be treated with the conventional seam annealing processes because the fine-grain structure is totally destroyed in the regions where the temperature has been raised high enough to convert the crystalline lattice to Austenite. New quench and temper annealing processes are being developed to deal with these materials and will be an important area for further research.

How Seam Annealing is Accomplished:

Seam annealing is performed as an inline part of the pipe making process. A set of medium frequency induction heaters and a reasonably long air-cooling zone are inserted in the HF pipe production line between the weld area and the final pipe sizing roll stands. The induction seam heaters raise the temperature of the weld zone to between about 950 degrees C (1750 F) and 1010 degrees C (1850 F) as measured by an optical pyrometer aimed at the outside center of the weld seam. The pipe is then allowed to cool slowly as it passes through the air-cooling zone. After it cools to below 700 degrees C (1300 F) no metallurgical changes will take place if it is water quenched. However, in practice, it is generally air cooled to below 370 degrees C (700 F) to avoid quench cracking. Below this temperature, the steel can be safely water quenched before passing though the mill's final pipe sizing section. An example of a typical seam annealing station is shown in Figure 5.

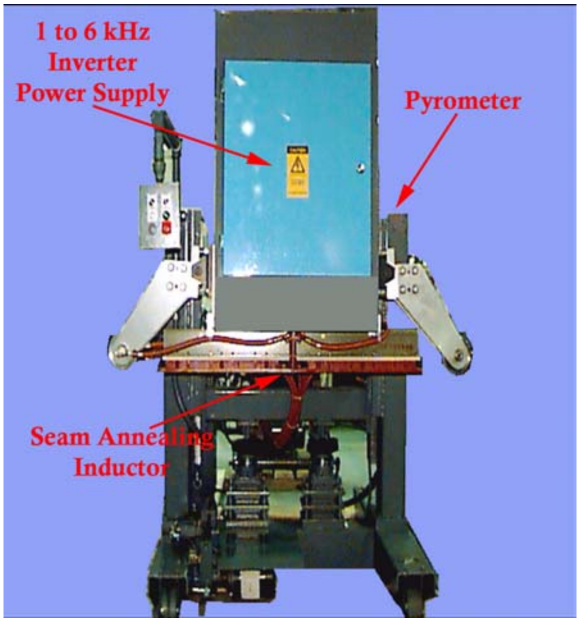


Figure 5 – Typical Seam Annealing Station

The induction heating portion of the process works in the following way. A medium frequency (typically between 1 kHz and 6 kHz) electric current is made to flow through a long electrical conductor that is suspended longitudinally over the weld seam of the pipe. The conductor is covered with a "U-Shaped" pole piece that focuses the current in the inductor on the surface closest to the pipe. The gap between the inductor and the pipe is nominally between about 6 mm (0.25 inches) and 9 mm (0.375 inches). For each heating section, the inductor is typically between 1.2 meters (4 feet) and 1.8 meters (6 feet) in length, between 19 mm (0.75 inches) and 40 mm (1.5 inches) in width, and designed to handle between 500 kW and 600 kW of power. Multiple heating sections are then placed in tandem to achieve the required power level and spaced to achieve sufficient "soak time". The inductor geometry is illustrated in Figure 6.

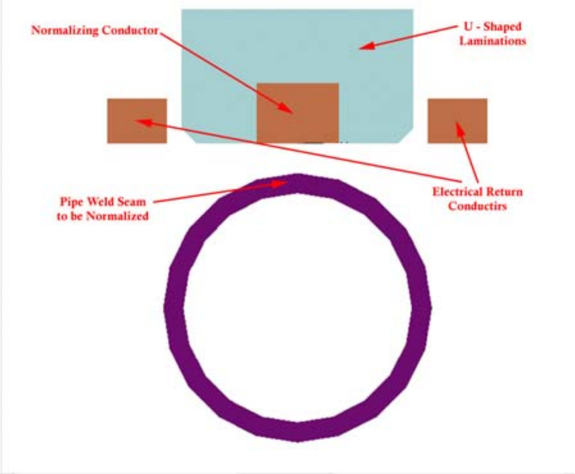


Figure 6 – Typical Seam Annealer Inductor Geometry

Because the inductor is very close to the pipe, a current is induced in the portion of the pipe that is directly under the electrical conductor because of the "Proximity Effect". What is the "Proximity Effect"? The nature of this effect is that AC currents produce time-varying magnetic fields, and time-varying magnetic fields at the surface of a conductor produce electrical currents in it. Thus the magnetic field generated by the current in the inductor's conductor causes a current to flow in the opposite direction in the surface of the pipe below it. The current in the pipe causes localized heating through its electrically resistive power loss (I^2R heating). The heating power is proportional to the square of the induced current, and the induced current is proportional to the magnetic field strength at the pipe's surface. Because the magnetic field decreases drastically as the gap between the inductor and the pipe is increased, maintaining a small gap is key to an efficient seam annealing process.

Seam Annealing System Design Considerations:

Designing a seam annealing system for a particular set of product wall thicknesses and mills speeds requires:

- Sufficient power to heat the seam to the normalizing temperature.
- An electrical frequency that insures good power transfer from the inductor to the pipe.
- A good balance between the rate of heating of the seam and the "soak time" necessary for the heat to flow to the inside wall of the pipe.

These factors in the system design will be discussed below.

Seam Normalizing Power Requirement:

Determining the over-all power requirement is relatively straightforward. The temperature of a material is really a measure of the energy stored in it per unit volume. The relationship is somewhat linear and the constant of proportionality is the volumetric specific heat. For example, to heat most steels from room temperature to 1010 degrees C (1850 F), 83,800 Watt–Seconds (Joules) per cubic inch must be imparted to the steel. For a particular production situation, the power that must be transferred to the seam is this number times the mill speed times the cross-sectional area to be heated (generally estimate by multiplying the pipe's wall thickness times the width of the seam annealing conductor). This is then divided by the efficiency of the power transfer process (65% is a very conservative efficiency that accounts for less than ideal setup) to determine to total inductor power supply requirement.

Electrical Heating Frequency:

The electrical heating frequency is determined from the "Electrical Reference" depth or the depth of current penetration in the steel. AC currents tend to flow on the outside surfaces of electrical conductors. A mathematical formula can be derived from the Laws of Physics that tells us how deep from the surface of a conductor the current is able to flow. This relationship tells us that the current flows deeper in a conductor at lower frequencies than at higher frequencies. It also tells us that the current flows deeper in a conductor when its electrical resistivity is increased or when its magnetic permeability is decreased. At first it would appear that lower frequencies would be better for seam annealing than higher frequencies, because the pipe wall would heat more evenly through its thickness. However, if the Electrical Reference Depth is too large, the power transfer from the annealing inductor to the pipe is very poor. The induction process transfers substantially more power when the depth of current penetration is less than the pipe's wall thickness.

At first it would seem that the best choice of electrical frequency would be when the "Electrical Reference Depth" is about the same as the pipe's wall thickness. However, the electrical resistivity of steel varies from a low value of 0.16 micro Ohm - meters at room temperature to 1.17 micro Ohm - meters at the final annealing temperature, or by over a factor of 7:1 as the steel's temperature increases from room temperature to the normalizing temperature. The change in "Electrical Reference Depth" caused by the temperature variation of electrical resistance is the square root of this, or about 2.7:1.

This is not the only change in "Electrical Reference Depth" that occurs during the process. While steel is reasonably magnetic at room temperature, it looses all its magnetic properties when heated above the Curie temperature (about 760 degrees C or 1420 F). Thus, at the Curie temperature, a drastic change in magnetic permeability (a factor typically between 10:1 and 20:1) occurs and this further increases the "Electrical Reference Depth".

For these reasons, the electrical heating frequency must be chosen so that at the higher process temperatures it is low enough to assure through heating of the thickest wall pipes, and yet high enough to insure reasonable power transfer between the inductor and the pipe for the thinner wall pipes. As a "Rule of Thumb" for most steels, 1 kHz is generally used for heating when the maximum wall thickness of the pipes to be normalized is above 12.7 mm (0.5 inches) and 3 kHz is generally used when the maximum wall thickness is below 9.5 mm (0.375 inches).

The temperature dependence of "Electrical Reference Depth" explains how the pipe wall heats as it journeys through the heating process. Initially, the Electrical Reference Depth is very shallow and the electric current is concentrated close to its outside surface. We call this "Surface Mode" heating (See Figure 6). The heating is very intense and the outside surface temperature of the pipe seam rises quickly. When this happens, the electrical resistivity increases so that the current penetrates more deeply into the surface of the tube. More of the tube wall is heated although now the current flow is more "spread out" and the heating is less intense. We call this the “Transition Mode (See Figure 7). When the Curie temperature is reached in an element of the pipe wall, and again this will happen at the outside of the pipe’s wall first, the Electrical Reference Depth suddenly becomes very deep. The current spreads out over the region of the tube wall above the Curie temperature but is more intense at the boundary between the material that is above and that is below the Curie temperature. When this happens, a very pronounced “channel” is developed in the material and this shape of this “channel” defines what material is, in fact, normalized. We call this the “Channel Mode” (See Figure 8). These three fundamental modes of the heating process are illustrated using the results of a thermally coupled, electromagnetic finite element (FEM) computer model in Figures 6 through 8.

The “Soak Time” Requirement:

This leads us to the discussion of “soak time”. Heating starts at the outside wall and progresses toward the inside wall as the material’s temperature increases. This happens at a rate determined by thermal conduction. Thermal conduction is a time dependent process. If we were to heat one end of a metal rod, the other end wouldn’t get hot immediately. Rather, a certain amount of time would be required for the heat to thermally conduct from one end of the rod to the other. This same phenomenon governs the amount of time necessary for heat induced at the outside of the pipe wall to travel to the inside of the wall. At the same time, the outside wall cannot be heated too quickly, because if the heat doesn’t flow toward the inside wall fast enough, the “grain growth” temperature will be exceeded at the outside wall. This limits the rate at which power can be transferred to the pipe. The rate at which thermal conduction occurs is determined by the material’s “thermal diffusivity”. This is the ratio of the material’s thermal conductivity divided by its volumetric heat capacity, and has the units of distance squared per unit time. It tells us that distance the heat travels is proportional to the square root of the time interval. As time increases, heat travels more slowly.

For steel, the thermal conductivity decreases as the temperature is increased, while the volumetric heat capacity increases with temperature. The net effect is that the thermal diffusivity is higher at low temperatures and the rate of heat transfer “slows down” temperature is increased. In summary, increasing both distance that the heat needs to travel (the pipe’s wall thickness) and the local temperature of the steel increase the amount of time necessary for the heat to reach the inside wall. The “Soak Time” available is the line length (as measured from the beginning of the first annealing inductor to the end of the last annealing inductor) divided by the mill speed. For these reasons it is generally the practice to adjust the power outputs of the annealing stations so that the pipe surface temperature exceeds the Curie temperature as quickly as possible. Subsequent annealing stations are then adjusted so that the exit temperature of the pipe’s outside wall from each station (as measured with an optical pyrometer) is 1010 degrees C (1850 F). When laying out a seam annealing line, the stations are

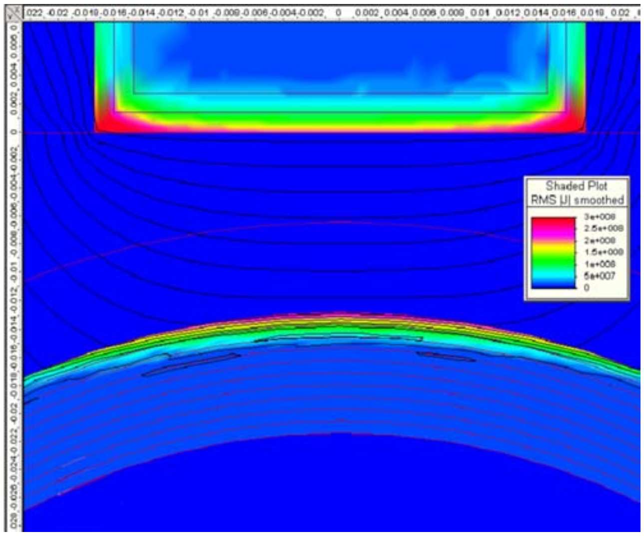


Figure 6 – Beginning Current Distribution in the Pipe when the Electrical Reference Depth is very shallow (The Surface Mode).

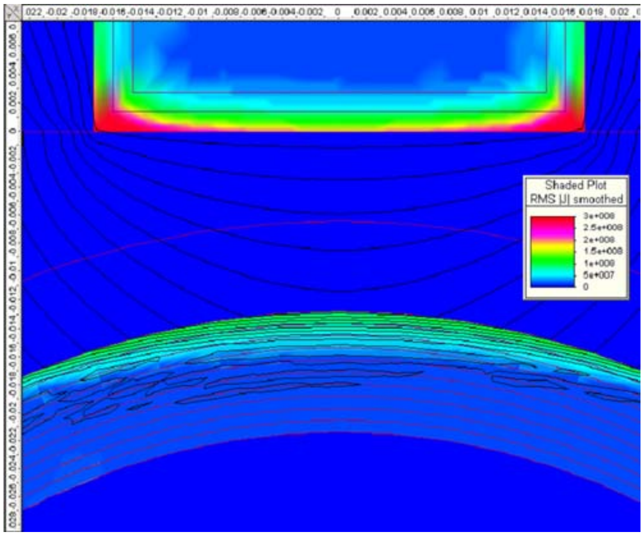


Figure 7 – Current Distribution in the Pipe after it has heated to below the Curie Temperature (The Transition Mode).

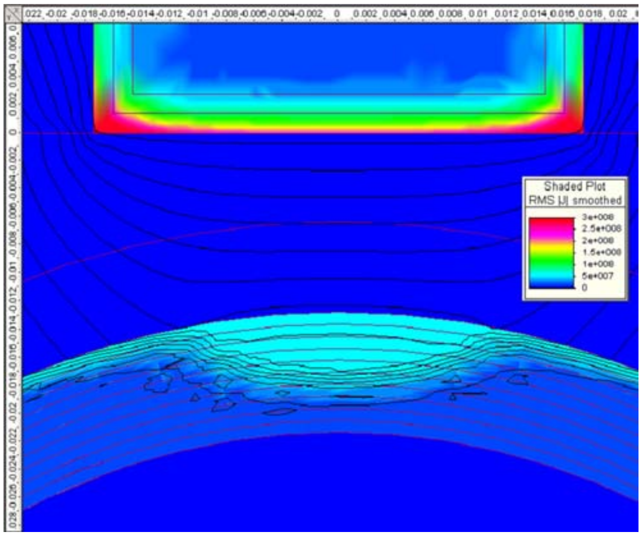


Figure 8 – Current Distribution in the Pipe when a portion of the seam is above the Curie Temperature (The Channel Mode).

spaced about one meter apart to allow additional “soak time” for the energy transferred to the pipe to leave its surface before addition power is applied. Detailed design of these lines for higher mill speeds or thicker pipes generally requires thermally coupled, electromagnet finite element computer modeling analysis to ensure they will perform to the specified requirements.

Conclusion:

The seam normalizing and tempering processes are an important part of the production process for making HF welded pipe to API specifications. These processes are surprisingly complex due to the interaction between the electromagnetic energy transfer and thermal conduction. Only recently, through the development of special finite element analysis computer programs and high processing speed PCs, have we been able to get an in depth understanding of these processes and develop the tools necessary to design systems for latest, high speed pipe mills. New, high yield strength, thermo mechanically processed (TMP) steels will require us to develop these processes further.