High Frequency Welding for Hydroforming Applications

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Introduction:

As automobiles have become more complex, and lighter weight to be more fuel-efficient, parts produced by the hydroforming process have become more prevalent. Hydroforming allows very complex shapes, thin wall and hollow parts to be produced that cannot be manufactured by other methods. Current applications include engine mounts, suspension frames, body structures, power-train components and exhaust system parts. These applications are illustrated in Figure 1 below:

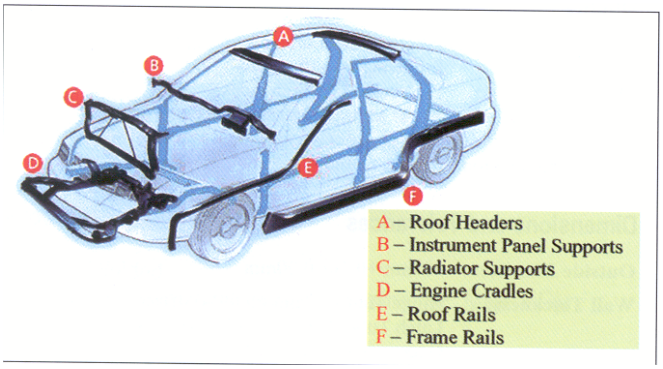


Figure 1 – Examples Hydroformed Automotive Components

Tube Characteristics Necessary for Hydroforming Applications

When producing a Hydroformed part, pre-bending and/or pre-forming may be essential before the start of the actual hydroforming process. After performing any prehydroforming steps, the actual hydroforming is accomplished by first placing the tubular blank into the closed cavity of a forming die. The ends of the tubular blank are then sealed, and the blank is filled with hydraulic fluid. The internal pressure of the hydraulic fluid forces the blank to conform to the shape of the tool cavity.

Designing a complex Hydroformed part is not easy. The initial tube blank is subjected to many complex stresses, and the wall stretches as the metal conforms to the die. A poorly designed part will have very low yields due to cracks and tears occurring during the forming process. Hydroforming dies typically cost around $100,000 a set, so “cut and try” type process development is not economically feasible. What makes hydroforming process development possible is Finite Element Analysis (FEM). During the design process sophisticated FEM models are evaluated in the computer and the part and blank geometries are adjusted until the model predicts a successful part.

For this reason final success depends on having tubular blanks with:

- Uniform material properties, and wall thickness.
- No surface defects that can cause stress risers and hence failure points when the part is formed.
- Minimum forming strain that is trapped in the finished tube.
- Higher Diameter to Wall Thickness Ratios (High D/t Ratios).
- Very repeatable characteristics from tubular blank to tubular blank.

Processes Used to Produce Tubes for Hydroforming Applications

There are three major processes used to produce tubes for hydroforming applications: Extrusion (Seamless Tubes), Folding and Welding, and Roll Forming. While this paper will focus on roll formed tubes, where the high frequency welding process is employed, we will touch quickly on the other alternatives.

Extruded tubes are made by heating a steel billet and then forcing the material through a die. They have the advantage that the material properties are circumferentially consistent throughout the tube wall. However, it is difficult to get good wall thickness consistency and the D/t ratios are generally limited to lower values than can be achieved by the other two processes. To obtain the higher D/t ratios required by most Hydroformed parts, the seamless tube must be further processed by drawing it over a mandrel (DOM process) to reduce the wall thickness. This subsequent process increases the cold working of the tube, which makes it less ductile and increases internal wall stresses. Also, because of the high capital cost, this production method is not as cost effective as the other tube making processes.

Folded and welded tubes are made from steel sheets. As the name implies, these are folded or otherwise formed into a closed shape and the edges are then welded together using laser, TIG, etc. Wall thicknesses can be very thin, resulting in high D/t ratio tubes, and material properties are very consistent except in the weld zone region. They have the further advantage that “tailored” blanks (sheets fabricated to have varying wall thickness) can be used and that the tubes do not have to have a uniform cross-section. However, this is a discontinuous process and therefore has the lowest productivity of the three discussed. It also has the disadvantage of relying on a melting type welding process where the modification of the material properties in the weld zone are more severe than with the high frequency forge welding process. The resulting weld bead is also more difficult to finish than with the roll form process.

Roll formed tubes are fabricated from a continuous steel strip. The strip enters a roll-forming mill and is successively formed, roll by roll, into a tubular shape. A

typical tube forming “flower pattern” is shown in Figure 2 and a tube mill for making high D/t ratio tubes is shown in Figure 3.

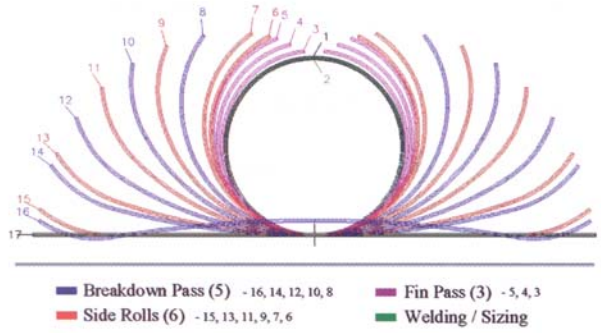


Figure 2 - "Flower Pattern" Illustrating the Steps to Form a Tube



Figure 3 - Typical High D/t Ratio Tube Mill

Roll formed tubes have the advantage that material properties are consistent everywhere except in the weld area, and even these can be controlled as will be explained later. Wall thickness is very consistent, and both external and internal weld bead scarfing can be employed to control the wall thickness in the weld area. The typical upper limit on D/t ratio is less than 40 and this depends on the particular characteristics of the mill and tooling employed. As with extruded tube, a subsequent drawn over mandrel (DOM) process can be used to increase the D/t ratio further. The work done on the final tube is not as severe because the

starting tube generally has a much higher D/t ratio than can be achieved with the extrusion process.

Welding Processes for Roll Formed Tubes

The most common processes used for welding roll formed tubes are laser welding and high frequency welding. While this paper will focus on high frequency welding, let's take a quick look at laser welding.

In the laser welding process, the final roll stands and weld box precisely condition and align the edges of the preformed tube. This requires very fine adjustment of the process and the use of precision strip. A laser is then used to heat the edges to their melting point, they joint and the tube is cooled while being constrained. Laser weld has the advantage of achieving a very narrow Heat Affected Zone (HAZ) and virtually no weld bead. It also has several disadvantages. First, laser welding is a melting type welding process and thus more severe changes occur in the weld zone than with the high frequency process. As shown in the micrograph below (see Figure 4), changes in Vickers hardness of 50% to 100% can generally be expected.

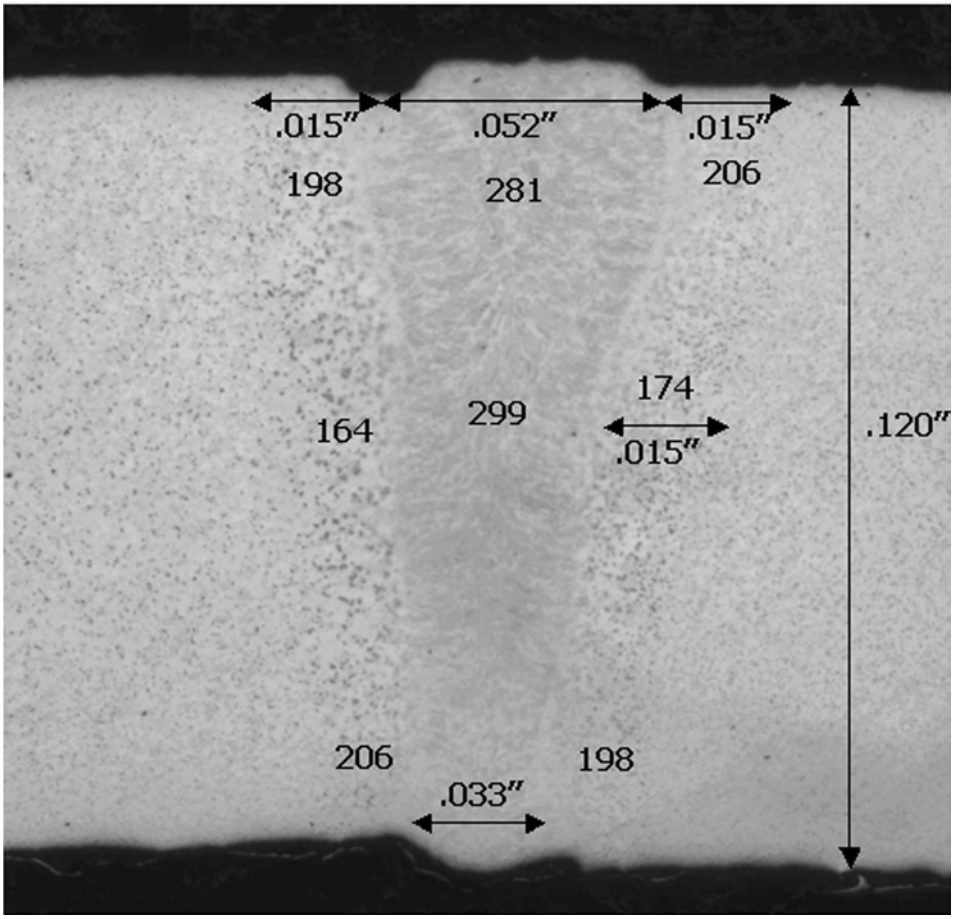


Figure 4 - Micrograph of a Typical Laser Weld Showing Vickers Hardness Measurements

For the same reason, the material structure in the weld zone is very different from that of the parent metal (again, see Figure 4). Finally, the process is considerably slower than high frequency welding and the initial capital investment is significantly more. Maximum weld rates for typical hydroforming tubes are less than 20 Meters per minute with laser welding.

High Frequency Welding

In the high frequency welding process, the preformed tube is passed through an induction coil excited by a high frequency (generally between 100 kHz and 400 kHz) electrical current. This is illustrated in Figure 5.

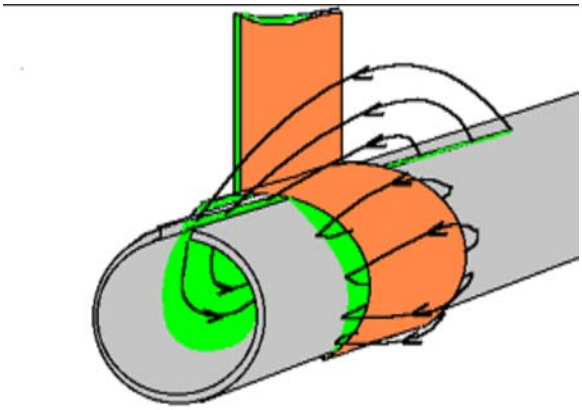


Figure 5 - The High Frequency Welding Process

The high frequency current in the induction coil creates a magnetic field that induces a current on the surface of the tube wall directly under it and flowing in the opposite direction of the current in the coil. In Figure 5, the black lines represent the magnetic field and the current is illustrated in green. The current induced on the tube's surface must follow a closed path. When it reaches the tube's open edges, a high frequency principle called the "Proximity Effect" causes it to close almost totally following the edges of the weld vee. The current concentration on the weld vee edges is much higher than on the tube surface under the induction coil because the current path is much narrower. In fact the current concentration is high enough to heat the vee edges to the tube material's forging temperature. The tube is then squeezed together at the vee apex by the tube mill's forge pressure rolls and a forge type weld is formed. A forge weld is much like that produced by a Blacksmith and has the advantage of having no cast structure as occurs with any of the melt weld processes such as laser welding. In fact the material properties of the forge weld zone can be controlled through proper choice of welding frequency and vee length! Finally, the other major advantage of the high frequency welding process is that it is very productive. Mill speeds between 50 meters per minute and 150 meters per minute are readily achieved for most tubes produced for hydroforming parts.

Controlling the Heat Affect Zone (HAZ)

Until just a few years ago, producers of roll formed, high frequency welded tube accepted any weld that passed the basic quality tests. Optimization of the weld zone only occurred when quality problems were encountered. When solid state welders started to replace the traditional vacuum tube welders, the issue of welding frequency attracted industry attention, because the early solid state welders operated at frequencies between 100 kHz and 200 kHz and the vacuum tube welders operated at frequencies between 300 kHz and 400 kHz. While both types of welder could produce acceptable product, it was observed that in some cases lower frequencies produced more desirable weld characteristics and in other welding situations higher frequencies produced a better performing weld. These observations spurred both analytical and experimental programs to determine how welding frequency affects weld characteristics. Finite element analysis plays a serious role in these investigations and a sample result from such analysis is shown in Figure 7. As can be seen from this figure, combining the temperature data with knowledge of the temperatures at which various metallurgical changes occur gives valuable insight into how welding frequency affects the characteristics of the Heat Affected Zone (HAZ).

While this research has only scratched the surface, what is now known is that choosing the optimal welding frequency and vee length can have considerable control over the characteristics of the Heat Affected Zone. This insight has lead to the development of variable frequency welders that are now commercially available. These allow the tube producer to precisely set the welding frequency from the welder's control console. Many tube producers are now using variable frequency welders to improve the weld quality characteristics.

Figure 6 shows how optimizing the welding frequency and vee length can produce a weld that has uniform hardness between the parent tube material and that in the weld zone. In fact, there is more variation in hardness across the wall thickness, probably due to the work done in forming the tube, than between the parent material and the weld zone. Also, the weld bond plane, indicated by the dashed line, is nearly invisible to the eye suggesting that the amount of untempered Martensite in the weld area has been minimized. This illustrates how controlling the Heat Affected Zone by optimizing the welding frequency can produce a superior tube weld.

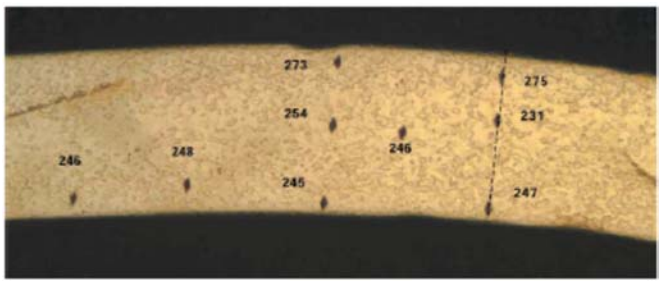


Figure 6 - Optimized Heat Affected Zone (HAZ)

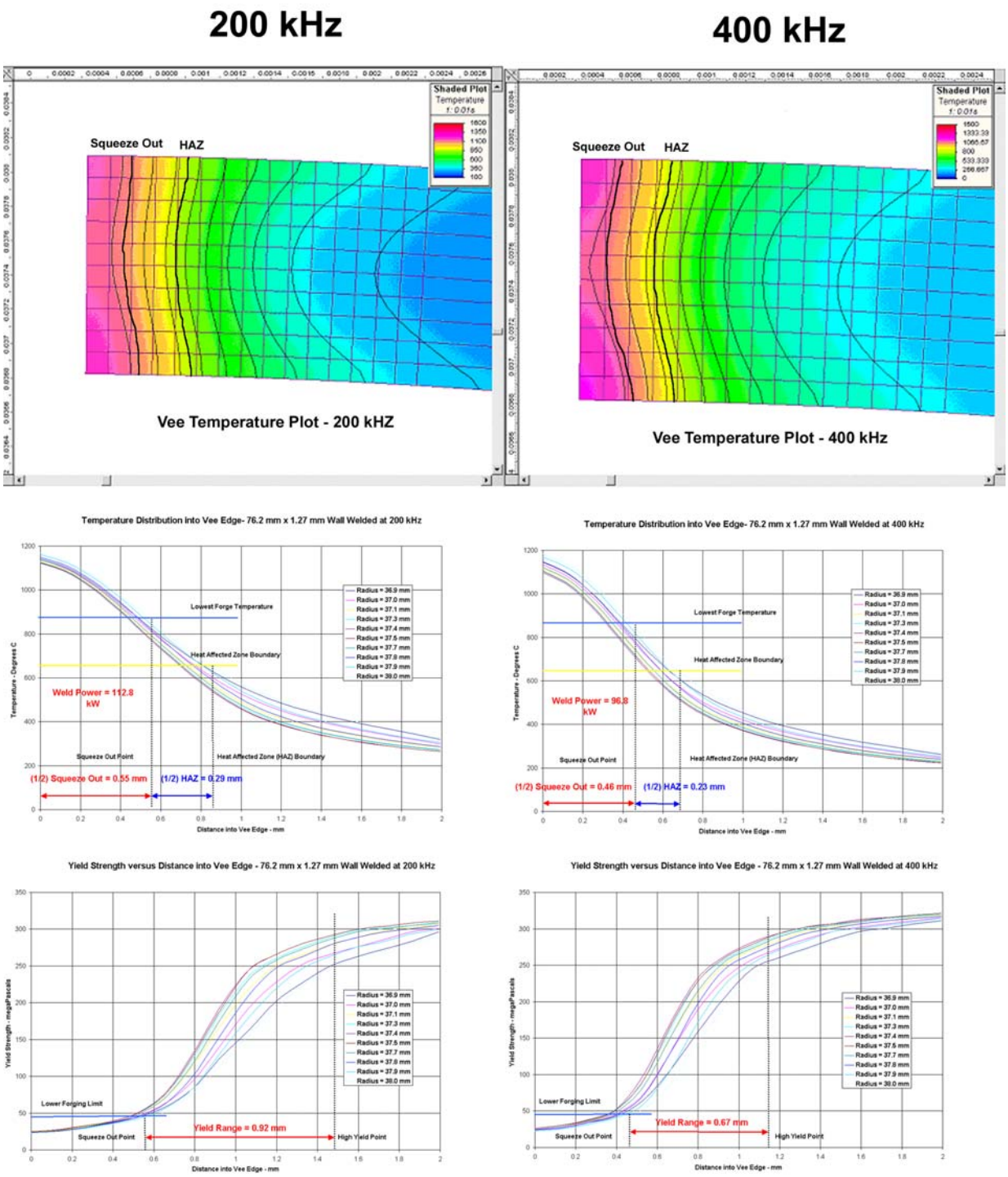


Figure 7 - Finite Element Results for Two Welding Frequencies

Seam Annealing

The Heat Affected Zone will be somewhat less ductile than the parent tube material, depending on the amount of untempered Martensite that is present. Fortunately, there is a well understood and in-line process called seam annealing that will eliminate any untempered Martensite in the weld zone. Figure 8 shows the weld area for the same tube produced on the same tube mill with and without seam annealing. The change in metallurgical structure is obvious. Seam annealing is used by all producers of petroleum pipe made to API 5L or 5CT and producers of pressure vessel tube to ASTM A53. Hence the process is well understood and the necessary equipment is readily available.

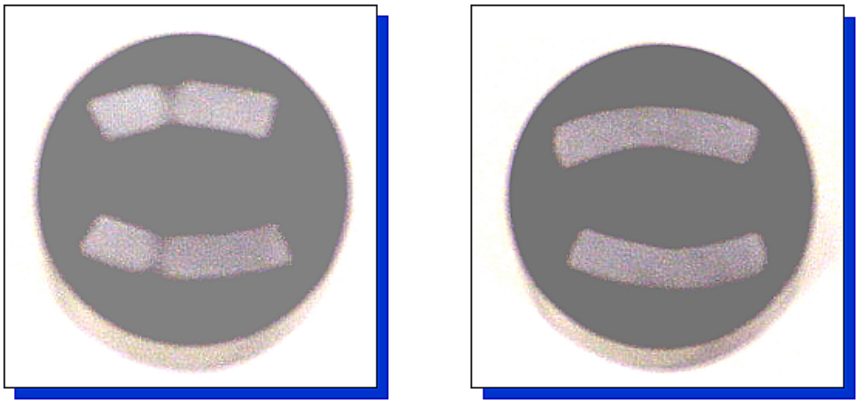


Figure 8 – Weld Zone Before and After Seam Annealing

In the seam annealing process, the weld is reheated inductively above the temperature necessary for the weld zone material to be in the Austenite zone. This temperature depends on the carbon content of the steel as is shown in Figure 9.

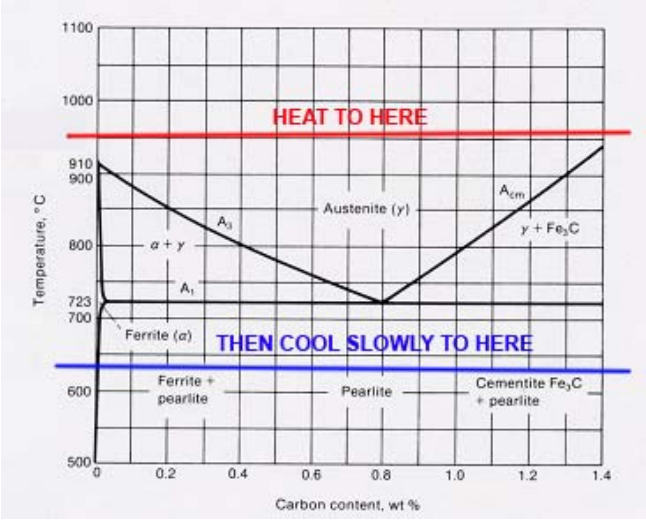


Figure 9 - Iron-Carbon Phase Diagram for Steel

The tube is then allowed to slowly air cool until the weld zone gets below the temperature at which no further changes in material properties can be expected. It then goes through a final water-cooling section and then the mill's sizing stands, which set its final dimensional characteristics. The equipment for heating the weld area is shown in Figure 10.

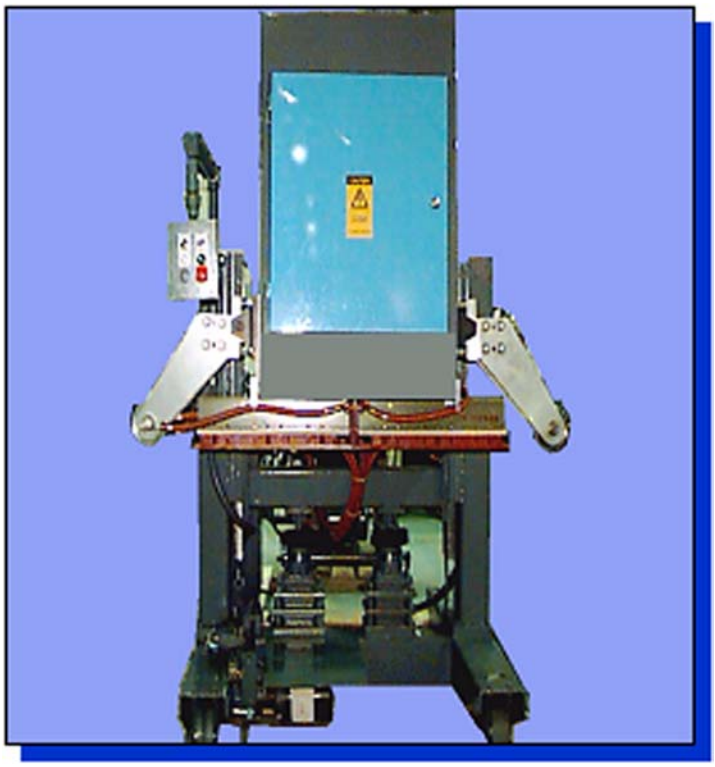


Figure 10 - Typical Seam Annealing Equipment

Producing High Frequency Welded Tube for Hydroforming Applications

With the background material given above, we are now ready to discuss how quality hydroforming tube can be produced using the high frequency welding process. Our first goal was to produce tube with uniform material properties and wall thickness. Starting with steel strip with the required thickness control eliminates the wall thickness concern in all but the weld area. The weld zone is reduced to the required thickness by scarfing the external weld bead. While internal bead scarfing is often employed, this brings with it the problem of setting the scarfing blade so it neither under nor over cuts the scarf. This, of course, affects the wall thickness in the weld zone. Also, the internal scarfing tool must be changed frequently, a contributor to mill downtime. Proper edge forming can force the weld bead to the outside surface of the weld zone. Selecting the best welding frequency has been shown to also control the height and smoothness of the internal weld bead. For many applications, correct usage of these two techniques can eliminate the need for internal bead scarfing. Uniform material properties can be achieved by choosing the optimal welding frequency by using a

variable frequency tube welder (Heat Affected Zone or HAZ Control). Seam annealing can also be employed to eliminate any untempered Martensite in the weld zone.

The goal of producing tube with no surface defects that can cause stress risers is accomplished by starting with strip with a good surface finish and using well designed, high quality mill tooling. Care should also be taken to insure the tooling does not mark the tube, and that the mill coolant is clean enough to prevent contamination of the tube surface.

The goal of forming a tube with the minimum trapped forming strain is accomplished by employing a mill designed for producing hydroforming tube. Generally mills that produce hydroforming tube have more roll stands than conventional tube mills and are more akin to roll forming mills. This allows a more gradual forming process and hence less forming strain is trapped in the finished product. The dimensional tolerances are also improved. Cage type forming has also been used to produce high quality tube for hydroforming applications with a minimum of trapped forming strain.

The goal of producing tube with the desired D/t ratio may already be accomplished. A mill designed for hydroforming applications should be capable of forming tubes with D/t ratios as high as 40. If higher D/t ratios are required, these can be achieved through a subsequent drawn over mandrel (DOM) process.

Finally, the goal of producing tubes with repeatable characteristics from tubular blank to tubular blank is a question of having good processes control and operating the tube making process in the center of the process window. Optimizing the welding frequency by using a variable frequency welder has been shown to have a profound affect on process repeatability. It has been proven that reasonably small changes in welding frequency has resulted in significant yield improvements particularly for harder to weld materials.

Conclusion:

If very practical to produce high quality tube for hydroforming applications using the roll forming and high frequency welding processes. However, not every mill can produce this tube, and the correct combination of equipment and tube making techniques is necessary to achieve the desired results. When HAZ control techniques are employed repeatable results from tube to tube are highly achievable.