Making HF Welded Tube for Demanding Applications

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Introduction

As pipe and tube makers explore new, higher product value markets, the demands placed on their tube making skills increases. Producing pipe and tube to meet API requirements, for automotive hydroforming or exhaust applications, or for high or low D to t ratio applications can require more careful process control, additional or new process steps, or new equipment.

This article will provide an overview of the requirements and ways of meeting them for four practical examples of demanding applications:

- Producing pipe to API specifications
- Producing tube for hydroforming applications
- Producing automotive exhaust tube
- Producing small diameter, low D to t ratio tube

Producing Pipe to API Specifications

One of the highest value products a pipe producer can manufacture is certified tube for petroleum applications. In the world market today, this generally means obtaining API (American Petroleum Institute) certification and meeting the criteria of API specification 5L for line pipe or 5CTfor casing, although several purchasers of these pipes have even more stringent requirements. Except for a few of the casing products, API allows the producer to use the ERW process and this is the most economical. The producer needs to be aware of the requirements placed on the pipe seam weld.

With the ERW process, the API specifications allow seam welding to be accomplished by either the contact or induction process. With the contact process, the 'arc marks'on the pipe that can result must be removed by a subsequent surface finishing operation. This reduces the wall thickness of the pipe in the reworked regions. However, there are API requirements concerning the minimum acceptable wall thickness in any region of the pipe. Those stated in API 5L Table 9 are given below in Figure 1, as an example requirement. It should be clear that the over aggressive removal of 'arc marks' results in scrap or pipe which must be sold for other applications.

While most quality producers of larger diameter API product use the contact process, there is a distinct trend toward using the induction process for large diameter API pipe because 'arc marks' are eliminated.

An issue when considering the induction welding process for large diameter API pipe production is the increased weld power requirement. While not a serious concern for the smaller API products, much of this production is for the larger diameter sizes (above 12"), and induction pipe welders with power ratings of 1000kW and above must be employed to achieve meaningful mill speeds.

Another issue when considering the induction process for the larger diameter API sizes is welding frequency. It is generally agreed that higher welding frequencies (above 200kHz) are best for the thinner wall thicknesses (below 12mm), and lower welding frequencies (below 200kHz) give a flatter hourglass shape and more edge penetration for the heavier wall (above 12mm) products.

In addition, lower frequencies for the same pipe size are generally used with the induction process, when compared with the contact process, because the weld vee lengths are longer. Longer weld vee lengths result because the induction coil must clear the entire profile of the weld rolls. The weld power requirement is increased because weld power increases with vee length and the reciprocal of welding frequency.

In the case of line pipe produced to API 5L, the choice of welding frequency is also influenced by the specifications. API 5L divides line pipe into to two Product Specification Levels (PSL), PSL 1 and PSL 2, with PSL 2 being the more stringent. In API 5L, Section 5.1.3.3.2 states that for PSL 2 grade pipe *'Electric welding shall be performed with a minimum welder frequency of 100kHz'*. For this reason, it is recommended that the welding frequency be chosen not lower than 120kHz to ensure this part of the specification is met over normal process variations.

It should be clear that welding frequency is an important factor in the pipe producing process parameters. Therefore, a stable and repeatable welding frequency is necessary to maintain consistent quality standards.

A last 'welding' difference between the contact and induction processes is the necessarily longer weld area with the induction process. In addition to longer vee lengths, this is due to the space

***Figure 1**: Typical API pipe minimum wall thickness requirement (from API Specification 5L, forty-second edition, January 2000, table 9)*

Size	Type of Pipe	Tolerance[a] (Percent of Specified Wall Thickness)	
		Grade B or Lower	Grade X42 or Higher
≤ $2\,^{7}/_{8}$	All	+ 20.0 – 12.5	+ 15.0 – 12.5
> $2\,^{7}/_{8}$ and <20	All	+ 15.0 – 12.5	+ 15.0 – 12.5
≥ 20	Welded	+ 17.5 – 12.5	+ 19.5 – 8.0
≥ 20	Seamless	+ 15.0 – 12.5	+ 17.5 – 10.0

required for the induction coil, and the space needed in back of the coil for enough impeder length to return the magnetic field. While all grades of API material are highly weldable, the yield strength increases with grade. Spring back of these higher yield materials can lead to poor edge presentation and vee shape, and these forming issues can provide serious problems for achieving good welds.

Increasing the length of unconstrained material between the weld rolls and the last fin pass clearly exacerbates these problems. While edge presentation problems can be severe enough to preclude achieving a good weld, they can often be cured through judicious mill set-up and particularly, adjusting the edge forming of the strip that occurs in the first two or three mill stands.

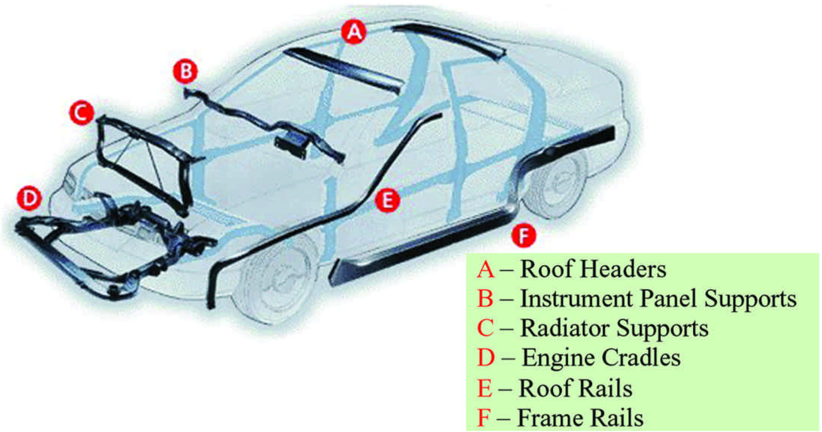
Finally, another factor that influences the weld quality of API pipe is the quality of the incoming steel. Continuous cast steel is preferred over ingot cast steel because ingot cast steel has a far higher likelihood of segregation. If when slit, the resulting strip exhibits segregation at one or both edges, these longitudinal cracks will curve upwards when the weld is forged in the weld rolls, and the results are defects known as ‘hook cracks’. ‘Hook crack’ problems are generally discovered as failures to pass the flattening test and are often mistaken as welding defects. They are, in fact, problems with the purchased steel.

Producing Tube for Hydroforming Applications

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 2.

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.

Figure 2*: Examples of hydroformed automotive components*



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, wall thickness, and no surface defects that can cause stress risers and hence failure points when the part is formed. Unrelieved forming stresses must also be minimized.

Two principle methods for producing tubular blanks for hydroforming are to use seamless tube or to use welded tube. Seamless tube has the advantage of uniform material properties but the disadvantage of relatively poor wall thickness consistency. Welded tubes have the advantage of excellent wall thickness consistency but the potential disadvantage of poorer material property consistency due to metallurgical changes and dimensional stability in the weld zone.

Of the various processes for welding tube, HF welding has the advantage in that it produces a forged weld and hence there is no cast structure in the weld zone. Cast structure occurs with any of the melt weld processes such as TIG and laser welding.

To produce the highest quality HF welded tube for hydroforming applications, one must start with the forming process. 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 stain is trapped in the finished product. The dimensional tolerances are also improved. Care should also be taken to ensure the tooling does not mark the tube, and that the mill coolant is clean enough to prevent contamination of the tube surface.

When HF welding these products, the shortest vee length and lowest welding power results in the narrowest Heat Affected Zone (HAZ). This defines the portion of material where the material properties are modified by the welding process. Recent results have shown that selecting the right welding frequency can control many properties of the Heat Affected Zone. Newly available variable frequency welders give the tube producer the ability to control the Heat Affected Zone (HAZ Control). This control can be used to minimize the variation in material properties that occurs in the weld zone.

Figure 3 shows how HAZ Control was used to minimize the variation in Knoop Hardness between the weld zone and the parent tube material. 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.

Finally, another concern with tube for hydroforming applications is controlling the height and smoothness of the inside weld bead.

While internal bead scarfing is often employed, this brings with it the problems setting the scarfing blade set so it neither under nor over cuts the scarf. Also, the internal scarfing tool must be changed frequently, a contributor to mill downtime. This, of course, affects the wall thickness in the weld zone. Proper edge forming can force the weld bead to the outside surface of the weld zone. Using HAZ Control to select 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.

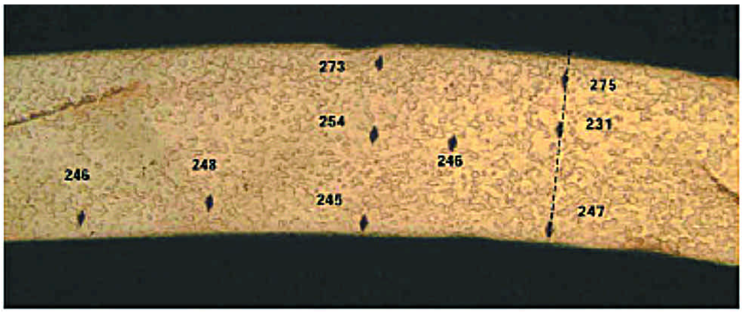


Figure 3*: Weld zone Knoop hardness of a HAZ controlled tube sample*

Producing Automobile Exhaust Tube

Over the last two decades, exhaust system designers have done extensive work to increase the durability of automobile exhaust systems. Many exhaust systems now last the life of the automobile, making replacement unnecessary. Most of this achievement has been accomplished by developing special metallurgies, mostly variants of stainless steel.

The major problem facing the exhaust system tube producer is that many of these new materials are difficult to weld. Further, subsequent bending operations to complete the exhaust component require the weld zone to have very high ductility.

Until recently, obtaining consistently good welds with the required ductility has been a serious problem for exhaust tube manufacturers, with slight changes in mill set-up causing significant decreases in yields. This process unpredictability puts serious pressures on the producers who must comply with automotive 'just in time' manufacturing. Also, as these exotic exhaust system materials are fairly expensive, high scrap rates must be avoided if the producer is to remain profitable.

The major breakthrough in recent years has been the discovery that the weldability of the new exhaust system materials is often very welding frequency dependent. Using the new, variable frequency tube welders, that allow the operator to set a precise and stable welding frequency at the control console, has allowed the exhaust system tube manufacturer to greatly improve welding process predictability and therefore increase yields and reduce scrap. This is accomplished by performing a carefully controlled process study when a new material is introduced to determine the best welding frequency.

Vee length and mill speed are other parameters that must be carefully chosen and controlled, as these determine the heating or 'soak' time. Heating of the weld vee is a balance between the Electrical Reference Depth, which determines how far the current penetrates the vee edges and is welding frequency dependent, and thermal conduction, which is time dependent. Manipulating both of these variables controls the temperature distribution in the vee edges at the weld forge point.

Depending on the particular characteristics of the material, a shielding gas may also improve weld quality. There are many types of shielding gases available and each has been developed for a particular class of materials. It is important to consult a shielding gas specialist when choosing a shielding gas. Also, application of the gas affects the process. The purpose of the gas is to remove oxygen from the weld vee. As oxygen is prone to adhere to the metal's surface, a 'gas shoe'or other form of nozzle can be used to free the oxygen from the surface.

A final concern is weld 'spume'. When metals having chromium content (such as stainless steel) are welded, tiny metal particles are ejected from the weld vee and form a continuous metallic shower or 'spume'. These particles can quickly build up on the surfaces of the mill tooling and induction work coil. They can lead to tube surface defects and work coil arc-outs. While the physics surrounding 'spume' generation is not clearly understood, the most plausible theory is that the particles are ejected from the near molten part of the vee closest to the forge point when the magnetic forces on the particles exceed the meniscus forces that try to hold them together. The magnetic forces increase with welding frequency, and it is known that 'spume' generation is reduced if the welding frequency is decreased.

Producing Small Diameter, Low D to t ratio tube

Applications for small diameter, heavy wall mechanical tubing continues to increase, particularly in the automotive, recreational vehicle, and farm/garden machinery segments. What makes this tube difficult to produce at competitive mill speeds is the impeder.

The weld power requirement increases with both mill speed and wall thickness. In order to transfer more power to the vee edges, the magnetic field in the vee must be increased. The magnetic field that passes through the vee is carried by the impeder to the region of the tube in back of the induction work coil so that it can finally close around the coil.

The impeder's saturation flux level and its temperature determine the amount of magnetic flux it can carry. The amount of flux an impeder carries is proportional to its cross sectional area, so that the smaller diameter impeders can carry less flux before they saturate. Above the saturation flux level, the impeder essentially becomes non-magnetic and the situation is not much different that if there was no impeder at all.

The impeder can also stop working if its Curie temperature is exceeded. Impeder ferrite impeder materials have Curie temperature between 150°C and 350°C, so exceeding the Curie temperature is a practical consideration. Heating of the impeder occurs due to losses that increase with the magnetic flux level. Impeders exhibit two types of losses. The first is due to I-R heating of the ferrite, where the magnetic field in the impeder induces a circular eddy current.

This loss is characterized by the electrical resistivity of the ferrite and its circumference. The second loss is due to the energy that is absorbed when the magnetic domains change orientation (which they do twice each welding frequency cycle), and is parametized by the coercivity of the ferrite.

With small diameter, thick wall tube, sufficient power must be transferred to the weld vee to obtain a good weld, however this must be accomplished using a relatively small diameter impeder. When dealing with this situation, the starting point is the selection of impeder material. It is important to choose that material that has the best balance between losses and Curie temperature at the chosen welding frequency. Unfortunately, lower Curie temperature ferrites also have lower losses and visa versa, so this choice is a complex one.

Impeder packaging is also important. Open-end impeders generally allow the impeder diameter to be increased by at least 1mm over the traditional, totally enclosed impeder designs. In either case, no metallic parts should be used in the impeder assembly as these will inductively heat, often causing burning of the casing. The case should be made from ferro-glass, which enhances the effective cross section of the ferrite.

Impeder cooling is very important. A high pressure pump should be installed in the impeder cooling system with enough capacity to insure at least 19l/mi (5 US gallons per minute) flow through the impeder assembly. The coolant needs to be extremely clean as contaminating particles can easily clog the small water passages in the impeder assembly. Ideally, the coolant should enter the assembly at about 10°C, as this is the temperature where most ferrite properties are optimum.

To minimize the magnetic flux the impeder must carry, as well as the over-all weld power necessary to obtain a good weld, the highest welding frequency should be used. Welding at 400kHz is usually recommended for fixed frequency welders used in these applications. However, 'bluing' of the tube is generally reduced at slightly lower frequencies and the inside bead also becomes smoother.

Several producers of small diameter, thick wall tube are now using variable frequency welders to optimize their processes. This is done by starting at a higher welding frequency and then reducing it until the most desirable weld properties are obtained, or to just above the point where the impeder starts to loose its magnetic properties.

When the impeder starts to lose its magnetic properties, the power required for achieving a good weld will increase drastically. Each tube mill and weld set-up has its own unique characteristics and hence its own best welding frequency.

Conclusion

To prove successful new, higher value added product markets, the tube producer generally must acquire new skills and techniques. There are 'tricks' and new techniques, such as HAZ Control with variable frequency welding that can be employed to achieve high quality production at competitive mill speeds. Both suppliers and the customer can provide helpful information and knowledge from other applications, to speed the development of a successful tube production process.

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