Optimizing Efficiency in HF Tube Welding Processes

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Modern solid state welders can convert 60Hz power to the high frequencies used for welding at efficiencies of 90%, compared to a maximum 65% for the older vacuum tube equipment. At the very best, improvements in welder design may raise this figure by another 5% or so. In contrast, the process efficiency is typically less than 20%, so this is where some worthwhile improvement can be realized.

If we calculate the amount of energy actually required to weld 1.5mm (0.065 in.) thick steel edge to edge at 100 meters per minute (325 fpm), it works out to less than 20 kW., however anyone familiar with induction welding knows that at least 100 kW. of HF weld power is normally required. 4/5 of the power generated by the welder is wasted in heating parts of the tube other than the desired heat affected zone, and in waste heat developed in the coil, the impedes, the weld rolls & the mill structure itself. The key to minimizing this power loss is to use proper setup of the coil, impedes & the tube mill itself.

High frequency tube welding is one of the most forgiving industrial processes, & it is possible to produce acceptable tubing for most purposes even with a hopelessly incorrect setup! The main incentive for proper setup of the welder is the amount of money that can be saved in electricity costs. Based on power costing 10 cents per kilowatt hour, a 400 kW welder operating 60 hours a week consumes $125,000.00 in electrical power each year. In many cases, power consumption can be reduced by 50% just by optimizing the welding process, saving tens of thousands of dollars a year. This kind of “fine tuning” usually improves product quality, reduces downtime & increases yield as well.

Why Choose a High Frequency?

If we were to apply 60 Hz. power to a pair of contacts positioned as shown in fig 1a, most of the current would simply flow around the back of the tube, heating the entire tube. Current will always take the path of lowest impedance (not necessarily resistance!). With DC & low frequency AC, resistance & impedance are pretty much the same thing. Technically speaking, at low frequencies, the impedance is dominated by its resistive component. As the frequency is raised, the magnetic fields resulting from the current flow start to affect its behavior, and inductive reactance becomes the dominant factor in determining impedance.

Both the current path along the edges of the strip to the apex, and the parasitic path around the circumference of the tube behave as inductors, & their inductive reactance increases with frequency, however the effect of frequency is much more pronounced on the circumferential current path.

Another reason for using a higher frequency is that in the case of induction welding, it is desirable to keep the size of the coil reasonably small. The coil & the tube form a transformer, with the coil being the primary winding, & the tube being a single turn secondary. The amount of power that can be coupled through a transformer depends on the strength of the magnetic flux, and the rate at which it changes (frequency). The higher the frequency, the less flux is required. This results in a coil with less turns & lower current. If it were possible to weld tubing at 60 Hz. power line frequencies, it would require a coil having hundreds of turns, carrying thousands of amps. A typical HF welding coil has 1 - 3 turns & carries a few hundred amps of current.

The higher frequencies also affect the behavior of the current that flows in the “vee”. As frequency is increased, the current tends to concentrate closer & closer to the edges of the strip. This is partly due to the “skin effect” (fig. 2) which causes current to flow on the surface of conductors at high frequency, and partly due to the “proximity effect” (fig. 3) which causes current on adjacent conductors to concentrate on the adjacent surfaces. Both of these effects are caused by distortion or interaction between the magnetic fields.
associated with the current flow. The combined skin and proximity effects result in less metal being heated, using less current, which translates into higher efficiency.

Frequencies used for tube welding range from roughly 100kHz to 800kHz, with lower frequencies being used for large, heavy wall tube, and the upper range being used for small, thin walled products, especially those using non-ferrous material.

**Efficient welder operation**

The primary cause of low efficiency is incorrect coil & impeder position. When a voltage is applied (or induced) across the strip edges, current will flow in two main paths. The current that flows along the edges of the strip to the apex of the “vee” heats the strip to welding temperature. Current will also tend to flow around the inside circumference of the open tube. This heats the entire tube, and does not contribute to the welding process. With induction welding, the sum of these two currents also flows on the outside surface of the tube, as this is the return path that completes the circuit. Note that any current that flows on the inside surface also returns on the outer surface, resulting in twice the power loss! Power is proportional to the square of current, so a small increase in current results in a large increase in power.

The amount of current that flows along the vee & around the inside circumference depends on the impedance of these two paths (fig. 4).

Shortening the vee and keeping it narrow reduce its impedance. A longer vee also provides more time for heat to conduct away from the edges, so conduction losses increase as well. It is important to realize that vee length has more effect on the heat affected zone width than welder frequency!

Shortening the work coil & increasing the tube diameter both increase the impedance of the tube I.D. The I.D. impedance can be further increased by placing an impeder in the tube. Under ideal circumstances, this impedance is raised to a point where most of the current flows in the vee, but this is not possible with small tube diameters because of the limited space available for the impeder. The introduction of I.D. scarfing equipment also takes up space that might otherwise be available for ferrite.

**Edge presentation**

If the strip edges are not presented in a parallel fashion, or if they have burrs or irregularities that have not been completely planished in the fin passes, efficiency will suffer because a larger mass of metal must be heated before a wall-to-wall weld can occur. Bad edge condition also results in excessive squeeze out of molten material, causing a large & often irregular weld bead which must be trimmed off. Such a condition nearly always results in weld defects as well.

A common condition is that where the inside corners of the strip meet before the outside corners, as illustrated in fig. 5a,b&c. This occurs because both top & bottom surfaces of the strip had the same width when it was flat, and when it is formed into a tube, the inside surface must be compressed and/or
the outside surface stretched in order for the edges to become parallel. Usually both stretching & compression occur, & most of this takes place in the fin passes. If these rolls are worn, or improperly set, edge presentation will not be correct.

When the inside corners meet first, most of the current will flow along these corners because the vee length is shortened. This causes excessive heating & melting, which in turn produces a large & usually ragged inside bead. In order to get a weld that extends through the entire thickness of the tube to the outside surface, a much greater amount of weld power is needed.

Fig. 5d,e & f show the correct, parallel presentation of the edges & the resulting weld formation.

Roll design for proper edge presentation is beyond the scope of this article, however any roll manufacturer can provide assistance in this area.

**Vee length & angle**

From a pure efficiency standpoint, the vee should be as short as physically possible, in order to reduce conduction losses, and to direct the majority of the induced current to flow in the vee. In practice, there are several other factors that must be considered. In most installations, the vee length is determined by the size of the weld rolls. Many weld box designs are derived from those used for low frequency ERW, and the large side rolls force the coil to be positioned further from the apex than is ideal. Smaller weld rolls are certainly more efficient, but may require more frequent regrinds & bearing replacements.

Tube wall thickness also influences vee length. High frequency welding tends to heat the corners of the strip first, which is the reason for the familiar “hourglass” shape of the heat affected zone. If the vee is too short, the temperature distribution across the edges of the strip will be uneven, resulting in an incomplete weld, or overheating of the corners & possible decarburization of certain steels.

How do we define the vee length? Heating of the strip edges begins to occur prior to entry of the strip into the coil so the popular notion of measuring vee length from the exit end of the coil to the apex is obviously wrong. A more realistic method is to measure from the center of the coil to the apex. Using this model, vee length should be approximately equal to 1-1/2 times tube diameter. This can be reduced in the case of large diameter, thin walled tubing, and usually has to be increased in the case of tube sizes below 25mm (1inch) due to the mechanical constraints imposed by the weld rolls. It’s interesting to note that as the vee length increases, relative to tube diameter, more & more magnetic flux has to be carried by the impeder. In the case of small tubes, the relatively long vee accentuates the role of the impeder at the very point where the physical size of the impeder is limited by the space available within the tube. Ultimately it is this which limits the minimum tube size that can be economically welded using the high frequency induction process. It would be possible to weld 1/4” O.D. tubing if you could use 1/2” O.D. weld rolls!

The angle at which the strip edges meet (approach angle or vee angle) also affects efficiency. A smaller angle requires less weld power because the proximity effect is greater, concentrating more power at the surface of the steel. A small approach angle also reduces the magnetic flux in the impeder, and may be helpful in cases where impeder saturation is a limiting factor in weld speeds. Using too small an approach angle is detrimental because it may result in pre-arching. A small angle also accentuates any mechanical instability in the strip, caused by worn roll bores or bent shafts. The optimum approach angle for carbon steel is 3-4°. Stainless steels & most non ferrous metals weld better with approach angles in the 5-8° range.

The approach angle can be difficult to measure. One “quick & dirty” method that works surprisingly well is to slide a small twist drill or dowel towards the apex until it touches both sides of the open vee, then measure the distance from the drill to the apex. Solving the triangle for a base equal to the drill diameter & a height equal to the measured distance provides the approach angle. For a 3mm drill that stops 45mm from the apex, the angle is equal to 90 - (tan⁻¹ 45/3), or 3.8°.

**Figure 6**

**Impeder Design**

The primary function of an impeder is to increase the impedance of the parasitic current path around the inside circumference of the tube, thus diverting more of the available energy into the weld “vee”. Impeders also concentrate the magnetic flux created by current in the work coil, so that a greater amount of energy is induced into the tube. A selection of typical impeders is shown in fig. 6.

The design & placement of the impeder are among the most important areas in which efficiency can be improved. Impeders are critical components in the induction welding process, however since they are low cost consumable items, many buyers base their choice on price alone. Welder manufacturers have always used electrical efficiency as a major selling point for their particular brand of equipment, however in reality, there is only a difference of a few percentage points between the best and the worst on the market, and this can usually be seen only under carefully controlled laboratory conditions. In contrast, the selection of an impeder can affect weld speeds for a given power level by as much as fifty percent. This would increase the speed of a mill from 200 to 400 feet per minute without any increase in weld power, or if speed were kept constant, would cut power costs in half. Since the average annual cost of impeders for a single 2” tube mill is less than $8,000.00, “cheap” impeders are frequently a very costly item.

The life expectancy of an impeder is another important factor to consider. Most cost less than $25.00 each, but it takes an average of twenty minutes to change one. If downtime is only rated at a conservative $500.00 per hour, the cost of downtime is seven times the cost of the impeder itself.

The most important component in an impeder is the ferrite. Some manufacturers use a grade that is inexpensive, but is designed for use as antenna rods in portable radios, not for the high power density and high temperatures which occur in tube welding. Impeders are critical components in the induction welding process, however since they are low cost consumable items, many buyers base their choice on price alone. Welder manufacturers have always used electrical efficiency as a major selling point for their particular brand of equipment, however in reality, there is only a difference of a few percentage points between the best and the worst on the market, and this can usually be seen only under carefully controlled laboratory conditions. In contrast, the selection of an impeder can affect weld speeds for a given power level by as much as fifty percent. This would increase the speed of a mill from 200 to 400 feet per minute without any increase in weld power, or if speed were kept constant, would cut power costs in half. Since the average annual cost of impeders for a single 2” tube mill is less than $8,000.00, “cheap” impeders are frequently a very costly item.

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The position of the impeder within the tube is extremely important. Since magnetic flux can only enter the impeder through the open vee (it does not penetrate through the wall of the tube), an impeder is most effective if it is positioned close up under the faying edges. Unfortunately it is also most
vulnerable to damage in this position, so some compromise is usually necessary. A good rule is to position the impeder one strip thickness below the top inside surface of the tube. Most impeder installations on small mills make no attempt to support the impeder within the tube; it simply slides along on the bottom. Not only is it least effective in this position, it may wear out prematurely due to friction with the moving tube. Failure to support the impeder properly may also cause it to move up & down within the tube, causing the weld temperature to vary.

For best efficiency, the ferrite in an impeder should extend from the center of the coil to a point slightly past the apex, and an equivalent distance back from the coil toward the last fin pass. The minimum impeder length can be found by adding the weld roll diameter to the coil length, as seen in fig. 6. Using an impeder that is too short will cause a dramatic drop in welding efficiency. Some mill operators prefer to position the impeder “upstream” of the optimum position, particularly when welding materials that produce a lot of weld spume. Doing so may extend the life of the impeder, but it does so at the expense of increased power consumption. A better solution to the spume problem is to find out why it is occurring & if possible, eliminate the problem at its source, or use an impeder design that is more tolerant to spume.

Coil Design

Modern solid state (transistor inverter) welders are far more efficient & reliable than the vacuum tube equipment that they have replaced, however coil design for these welders is far more critical. Solid state welders are low voltage, high current devices, which contributes to their reliability but results in coil currents that may be five times higher than in older welders. Because power dissipated in the work coil itself is proportional to the square of current, (POWER=CURRENT$^2$ x RESISTANCE), even a small amount of electrical resistance in the coil can cause a huge increase the power wasted heating the coil itself.

As an example of this, a typical solid state welder may generate a coil current of 1500 amps. Even with a coil resistance as low as 1/100Ω, this translates to a power loss in the coil of 22.5 kilowatts! This can easily negate any gain in the efficiency of a solid state welder, over that of a vacuum tube type. The coil losses in a comparable vacuum tube welder would be less than 1 kilowatt. Typical coils for both solid state & vacuum tube welders are shown in fig. 8.

Work coils for solid state induction welders normally use wide bands of pure, oxygen free copper, with cooling tubes brazed to the outside, to minimize their electrical resistance. Normally these coils have only one or two turns. Because solid state welders deliver a lower voltage to the coil, the coil inductance must be lower. This often means that the coils must be made longer, thus increasing the effective vee length & reducing the efficiency of the welding process. Proper coil design requires a thorough knowledge of the welders matching requirements, as well as the induction welding process itself.

Distance "B" is the effective vee length & should be kept short for maximum efficiency. This requires that "C" & "D" also be minimised. "F" is the ferrite length & should be twice "B" or greater. "G" is the weld coil I.D. & is normally 1.2-1.5 times tube O.D. (A). "E" should be at least 1.25 times "F".

Figure 7

It is important to follow the welder manufacturers recommendations as to coil design, and in many cases the additional cost of buying coils from the manufacturer or another dependable source is more than offset by the reduction in power consumption that these coils can provide.

Welder Frequency

The term “high frequency”, when applied to tube welding, can mean anything from 80kHz., to over 800kHz. Although frequency within this range has little direct effect on the width of the heat affected zone, & thus upon the quantity of metal heated, there are several indirect effects which relate to efficiency.

Impeders are more effective at the higher frequencies, however their losses increase with frequency, so keeping them cool can be difficult. The welders themselves also convert power more efficiently at lower frequencies, and the lower coil voltages reduce the likelihood of flashovers.

Higher frequencies are better suited to small diameter tube production, whereas lower frequencies are a better choice for larger tube & pipe. The ideal situation is one in which the welder frequency can be adjusted, & this type of equipment is now available from several manufacturers.

Summary

High frequency tube welding is the most widely used method of producing welded pipe & tubing, and the most efficient in terms of cost. Because profit margins are fairly small in the tube & pipe industry, even a small increase in efficiency can make a big difference to the “bottom line”. Not only will there be direct savings in power costs, but product quality & yield will usually increase as well.

Even downtime & maintenance costs are reduced by operating an induction welder efficiently, because the equipment is not working as hard to produce the same production output.

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