PRINCIPLES OF HIGH FREQUENCY INDUCTION TUBE WELDING

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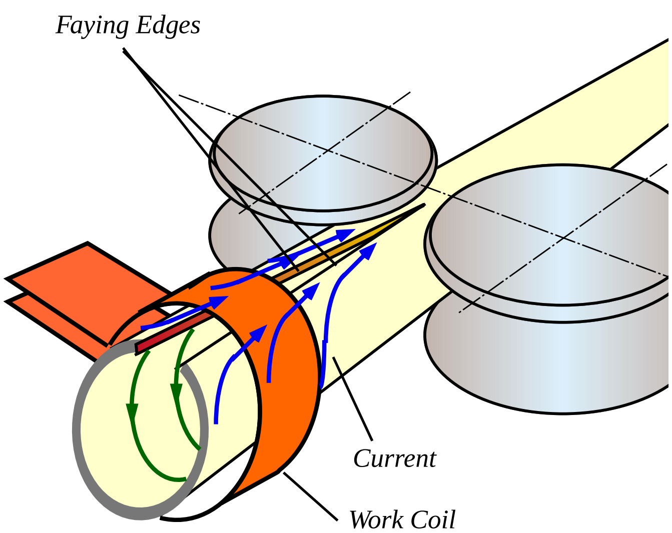
Introduction

High Frequency induction welding accounts for the majority of welded tubing produced worldwide, yet it is still a largely misunderstood process. Part of the reason is that the process is very forgiving, however a thorough understanding of it can lead to higher product yields and quality.

Principals of operation

Induction welding is a form of Electrical Resistance Welding (ERW) in which the large rotary transformer common in low frequency ERW is replaced by a "virtual transformer" consisting of the work coil (primary winding) and the tube itself (secondary winding). A ferromagnetic core inside the tube has a similar role to the laminated iron core in a conventional transformer.



Current flowing in the coil causes a magnetic field to develop surrounding the coil, part of which intersects with the open tube. This causes an electric field on the outer surface of the tube which in turn creates a voltage difference across the edges of the strip. At the frequencies used for induction welding, the interaction between electric and magnetic fields can cause currents to flow in unexpected ways. The "skin effect" confines current to within a few thousanths of an inch of the surface, so the voltage across the strip edges tends to cause current to flow circumfrentially around the inside surface of the tube *in the opposite direction* to the induced current on the outside surface.

Because the faying edges of the strip are in close proximity to one another from the coil to the apex of the vee, they have a very low value of inductance, and it is inductance rather than resistance that governs current flow at high frequencies. This is sometimes refered to as "proximity effect".

It can be seen from this that there are two main paths along which current can flow when a voltage is applied or induced across the edges of the strip. The key to operating a high frequency welder efficiently is to direct the majority of the current along the faying edges where it does useful work in heating them, and minimise the wasteful parasitic current that flows around the inside surface of the tube.This is done by making the impedance of the vee low relative to that of the I.D. surface.

Function of impeder

The first tool we have is called an impeder because it raises the impedance of the tube. An impeder is simply a bar of ferromagnetic material placed inside the tube within the weld area. Such materials have the effect of raising the inductance of a circuit surrounding them. The resistance of the inside surface of the tube is extremely low but at high frequencies, it is inductance (or more specifically inductive reactance) that is the primary factor in determining current flow. The sum of reactance and resistance is known as impedance. This is the "classic" explanation of how impeders work, but there are two additional factors involved:

Materials such as ferrite "conduct" magnetic fields in a similar way to that in which metals conduct electricity. This is known as magnetic reluctance, and is analagous to resistivity in metals. Although little or no magnetic field penetrates the wall of the tube (at least in the case of ferritic (magnetic) tubing), some flux does enter the ferrite through the open vee. The low reluctance of the ferrite causes some flux to be drawn into the impeder, and because there is now flux inside the tube as well as outside, a corresponding electric field is induced on the inside surface of the tube. This field has the same polarity as the field on the outer surface, so the inductance of the inside surface further increased.

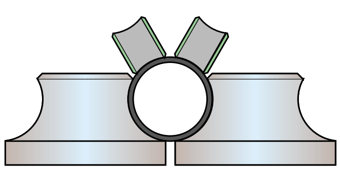
There is yet a third method in which impeders improve the efficiency of induction welding. The work coil & the open tube constitute a transformer, albeit a very poor one. Not all of the flux that results from current flowing in the coil is common to the tube (or secondary winding in our virtual transformer). This stray flux is represented in transformer design as leakage reactance, and it has exactly the same effect as an equivalent amount of ordinary reactance placed in series with the secondary. When current flows through a reatance, a voltage drop occurs. In this case, the voltage drop is across the edges of the strip, so more & more current must be forced through the work coil to maintain the voltage across the strip.

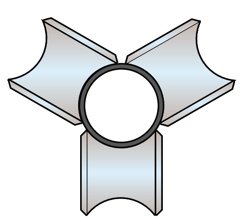
Because ferromagnetic materials “conduct” magnetic flux far better than air, the presence of an impeder in a tube causes more of the coil flux to intersect with the tube, so leakage reactance is reduced.

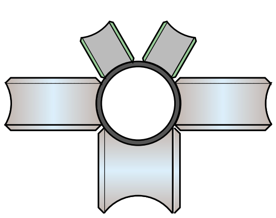
Familiar ferromagnetic materials such as iron, nickle & chromium are a poor choice for impeders because they have very low electrical resistivity. This results in large eddy currents being induced in them, causing uncontrolled heating. Ferrite is a man made substance having magnetic properties similar to iron, but much higher resistivity. Some eddy current heating still takes place, but it is much less than would be the case with pure metals, and cooling requirements become manageable.

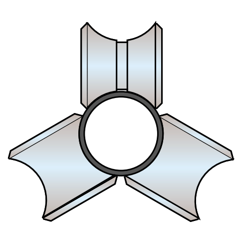
Weld roll arrangements

The induction heater just heats the strip edges. The actual welding occurs as a result of material flow resulting from pressure applied by the squeeze rolls. This section of the tube mill offers one of the greatest challenges to the mill designer. The weld pressure unit (or weld box) not only has to provide a very high degree of precision, but it also has to be strong enough to withstand unwelded tube being forced through it. It is the only section of the mill subjected to high temperatures & thermal shock, and to further complicate matters, induction welding geometry requires that the rolls and supports be as small as possible.


A: FOUR ROLL


C: THREE ROLL


B: FIVE ROLL


D: THREE ROLL INVERTED

Nowhere in the mill is there as much variation in design philosophy as there is in weld box arrangements. Early designs were derived from low frequency ERW, with massive lower rolls on cantilevered shafts & smaller head rolls. This arrangement is still widely used on large mills. (A)

The five roll box (B) is a variation in this desgn that adds a fifth roll at the bottom of the tube, allowing smaller diameter side rolls to be used.

Many smaller mills use three rolls mounted 120 degrees apart. Some are orientated with a grooved roll at the top of the tube (D), others with a roll directly below the tube. *D* eliminates edge misalignment and is especially suited to D/T ratios above 10:1. *C* provides a means of compensating for edge misalignment caused by camber in the strip, and is more frequently used wither lower D/T ratios. Both methods work well, and some weld boxes can be inverted, allowing either configuation to be used.

Some three roll boxes are designed around standard 3 jaw lathe chucks. This permits all three rolls to move in or out as a unit, however it also raises or lowers the metal line due to vertical movement of the lower roll(s).

For very small diameter tubing, a two roll weld box is often the best. These are the simplest both in construction or setup, but difference in surface speed between the rim & the root of the rolls is greater than with other roll arrangements & this can lead to swirl marking of the tube. Two roll boxes can be made with the bearing blocks staggered, allowing the use of very small diameter rolls, however keep in mind that the smaller the roll diameter, the greater the rotational speed. Since the same pressure is needed to create a weld upset with all roll configurations, small rolls will have shorter bearing life.

Vee Length

Vee length depends on coil position, and to some extent on coil length, since heating starts to occur even before the strip enters the coil.

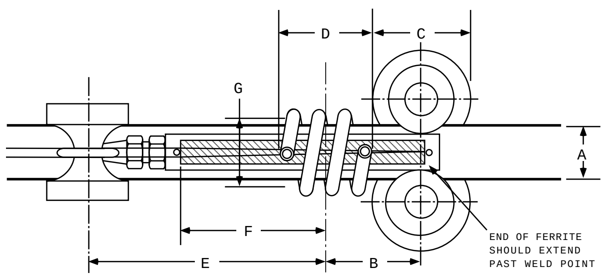
Coil position is usually determined by the diameter and size of the weld roll box, whereas coil length is generally dictated by the matching capabilities of the welder.

There are two factors involved here:-

1 The high efficiency of induction welding is due to the fact that only a very small mass of metal is

heated. Increasing the vee length allows more time for heat to be conducted away from the edges, so more energy is needed & a wider heat affected zone results.

2 The distribution of current between the vee and the inside surface of the tube depends on the relative impedances of the two circuits. A longer vee has a higher impedance, which directs more of the available current around the inside of the tube. This is particularly important when welding small diameter tubing, since the small space available for impeders limits their effectiveness.



A	TUBE O.D.	
B	EFFECTIVE VEE LENGTH	MINIMUM
C	WELD ROLL DIA.	MINIMUM
D	COIL LENGTH	MINIMUM
E	FIN PASS TO COIL CENTER	2x VEE LENGTH MINIMUM
F	FERRITE AHEAD OF COIL CENTER	1 to 1-1/2 x VEE LENGTH
G	COIL I.D.	1-1/4 x A (MAX 1"OVER TUBE DIA)

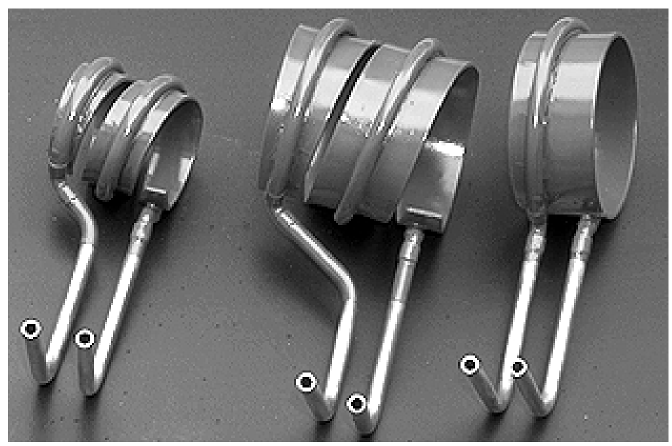
There are several schools of thought regarding optimum vee length, but all agree that minimum electrical power is used with short vee lengths and short work coils. Power distribution across the edge face of the strip is fairly even, however there is less thermal conduction away from the corners, which may result in their overheating before the center of the edge reaches forging temperature. This tendency can be reduced by increasing the vee length, or by lowering the welder frequency (more on this later), so optimum vee length is more a function of wall thickness than it is of diameter. As a general rule, I recommend using a minimum length vee & the shortest practical work coil unless there is evidence of uneven temperature distribution. If the weld tends to be cold in the center, the coil should be moved back the minimum distance needed to correct the problem.

Because the weld rolls are usually made of steel (D2 or H13), they will heat up readily due eddy currents induced in them by the work coil. This sets the minimum acceptable clearance between coil & rolls. Non magnetic (ceramic or Ampco 25 bronze) or weakly magnetic (Tungsten carbide) rolls will reduce roll heating.

Approach angle

The closer the faying edges are to each other, the lower their inductance will be. This reduces the total impedance of the vee, relative to the parasitic current path around the inside tube surface. There is a limit to how small a vee angle can be used. As the angle is reduced, any mechanical instability such as “breathing” will cause a greater change in vee length, and therefore in weld temperature. In addition, at high levels of induction, the voltage across the vee can be sufficient to ionize the air between the edges, causing arcing. A lower frequency helps because it reduces the voltage, but there is still ultimately a mechanical limitation of about 2-3 degrees for carbon steel tubing and 5-8 degrees for stainless & non ferrous materials.

Work coils



Current flowing through the work coil establishes a magnetic field that causes energy to be induced into the tube. Coil current increases with weld power & decreases with frequency, but at any frequency used for induction welding, the currents are in the order of hundreds, to thousands of amps. This current all travels close to the coil surface due to the high frequency skin effect, so coils must be designed and made to handle these extremely high currents with minimum losses. We have seen solid state welders with quoted efficiencies of 90% or better degraded to less than 60% because of poor work coil design. Vacuum tube welders are more forgiving of poor coil construction because most operate at higher voltages & lower currents, but well designed & manufactured coils will still save thousands of dollars in energy costs each year.

Coil Position

Coil position depends on vee length, which we have already covered in some detail. The coil should normally be posititioned as close to the weld rolls as possible without induction heating them or their support structure. Many people believe that a left to right mill should use clockwise helix coils & a right to left mill should use counterclockwise helix. In most cases the helix direction is of no consequence but in a few installations, one helix direction may keep the coil leads further away from the rolls & bearing blocks, resulting in less heating. This occurs more with 4 roll weld boxes where the head rolls are smaller than the side rolls. The coil is usually axially centered around the tube, although some operators set the coil high so that there is more clearance at the top. This has little effect on performance.

Coil length

From a purely electrical standpoint, a coil has its highest efficiency when the length is equal to the diameter. In induction tube welding, a longer coil starts to heat the strip edges further from the weld point, so more energy is lost to thermal conduction. As a result, short coils are preferable. Having a coil that is too short may raise its inductance to a point where it can no longer be matched to the welder. This will limit the maximum power that can be delivered from the welder to the coil. If the welder hits an over current limit before it reaches full voltage, the coil impedance is too low & turns should be added, or the length should be reduced. If a voltage limit is reached first, the impedance is too high & turns should be removed or the coil lengthened. A shorter coil has a more narrow cuurent path, so it's resistance will be higher. This will lead to higher I^2R looses in the coil. At very high power levels, using too short a coil may also lead to heating of the tube body, since current flowing in the vee also has to flow around the outside surface of the tube. A short coil forces this current into a smaller area, once again increasing I^2R looses.

As a general guide, making the coil length equal to tube diameter seems to work well for D/T ratios of around 10:1. Shorter coils increase efficiency with higher D/T ratios & longer coils may benefit lower D/T ratios, provided that the overall vee length can be kept short.

Number of turns

Most modern welders have some built in matching network that allows them to operate efficiently into a fairly wide range of coil impedances. Vacuum tube oscillators typically have a higher output impedance than solid state types, so the coils are generally of lighter construction and have more turns. Coils for transistor oscillators are usually single or two turn types and operate at lower voltage & higher current levels.

A typical single turn coil on a solid state welder may carry several thousand amps so it is imperative that all connections and joints be capable of carrying these high currents. At 2500 amps, even 1/1000 of an ohm of resistance results in over 6kW being dissipated!

Most welders have to accomodate a wide range of tube sizes. As tube diameter decreases, so must the coil diameter and at some point, extra turns must be added to keep the coil inductance within the range of the welders matching circuit. Electrically there is no such thing as a fractional number of turns & going from a single turn, to two turn coil of the same diameter & length results in an almost fourfold increase in coil inductance. With many welders, this will exceed the matching range in the opposite direction, so the two turn coil is often made longer than it should be to reduce its inductance. While permitting a proper impedance match to the welder, this increases the effective vee length, so overall welding efficiency drops.

Impeders

The very first impeders were bundles of soft iron wire. Although they worked in the sense that they diverted more power into the vee, the electrical eddy curent losses in the impeder cores limited their use to very low power levels & frequencies. Fortunately a better material exists. Ferrite is a ceramic material composed of oxides of iron and other divalent metals. Because there are oxygen atoms present in the crystal lattice as well as metals, the electrical conductivity is much lower than that of pure metals, and the magnetic characteristics are also somewhat improved.

Type of ferrite

Early ferrites used oxides of iron and nickle. These were designed for higher frequencies and much lower power levels than those present in induction welding, so they don't offer optimum performance. Ferrites based upon oxides of iron, manganese & zinc have lower magnetic losses and can operate at much higher power levels.

Cooling requirements

A theorectically perfect ferrite would not require any cooling but unfortunately we are not quite there yet. Modern ferrites are much improved over those available a few years ago, but even the best are not perfect insulators so some eddy current heating occurs. Eddy current heating increases with the square of frequency, so doubling the frequency increases these losses fourfold. Energy is also absorbed in changing the orientation of the magnetic domains in the ferrite and this energy is released as heat as well. Losses occuring due to this are known as hysteresis losses, and are directly proportional to frequency, and to the coercivity of the ferrite material.

At 400 kHz., typical manganese/zinc ferrites have maximum total losses (eddy current + magnetic hysteresis) of 5-10kW per kilogram, although some newer types have as little as 1kW/kg. A core used in a 3/4" impeder weighs 6 oz. or 170 grams., so it could dissipate as much as 1700 watts, making liquid cooling virtually a requirement. At this power level, one gallon per minute of water would be required to continuously remove 1700 watts with a 15 degree temperature rise.

Flow types

Most impeders are cooled by water or mill coolant which enters through a threaded coupling at one end, & discharges into the welded tube after cooling the ferrite. Some impeders may have an internal stainless steel tie rod so that an I.D. scarfing or bead rolling head can be supported. Hollow impeders are also available for applications where an existing I.D. tow rod or other internal tooling needs to be passed through the impeder.

There are a number of manufacturing processes that require that the tube a clean & dry I.D. These include conduit, certain types of automotive & refrigeration tubing, aluminum & stainless steel tubing, and any tubing which is produced in continuous lengths, rather than cut as it exits the mill. For these applications, return flow water cooled impeders are available in sizes as small as 8mm (0.315”). Most return flow impeders use a coaxial coupling, so that coolant enters & leaves through a single fitting.

Various attempts have been made to cool impeders with air or nitrogen, but the high coolant flow requirements make these impractical or uneconomical in most cases. An impeder that requires one gallon per minute of cooling water at 60 degrees F, would require several hundred cubic feet per minute of air to achieve the same cooling effect. Chilling the air or nitrogen will reduce the flow requirements, but ferrite works best in the 80-150 degree range, and cooling it excessively actually increases the rate at which heat is generated, as well as reducing the magnetic permeability of the material. Air or gas cooling may become a practical reality as better grades of ferrite are developed, but with the present state of the art, it has severe limitations and its high cost limits its use to a few applications where liquid cooled impeders cannot be used.

Ferrite position

For optimum efficiency, the ferrite rod in an impeder should extend from the centerline of the weld rolls, through the coil and at least a similar distance on the entry side of the coil. Minimum ferrite length should be twice the distance from the weld roll centerline to the work coil centerline. Having the ferrite longer will improve efficiency up to point, but there is little to be gained by increasing this length by more than 50%.

If the ferrite does not extend all the way to the apex, there will be a large reduction in efficiency, however there are a few situations where the addition weld power required may be justified in exchange for longer impeder life. Having the ferrite as little as 1/4" short of the apex can increase power requirements by as much as 25%.

The vertical position of the ferrite within the tube is important as well. Many operators allow the impeder to lay in the bottom of the tube, however it is least effective in this position. The ideal position is as close to the strip edges as possible, but it is more vulnerable to damage here. A good compromise is keep the impeder one strip thickness below the top inside surface of the tube.

The ferrite must not extend toward the mill entry end so far that it passes through the centerline of the last fin pass or seam guide. Doing so will cause large induced currents to flow "upstream" and through the fin or seam guide. It is important to note that a second "vee" exists upstream from the coil, since the last fin or seam guide electrically connects the strip edges. Insulating the seam guide has little effect because the insulation just forms a capacitor and at high frequencies, current will still flow. The length of this second vee should be at least twice that of the primary vee.

Impeder failure

All impeders fail eventually & have to be repaired or replaced. Nothing gets "used up" but the environment is so hostile that they have to be considered as expendable components. Having said this, it is obviously desireable to get the longest possible use out of each one.

The main cause of damage to impeders is poor edge presentation. Not only does this require excessive heat to achieve a reliable weld, but it also increases the height of the inside weld bead.

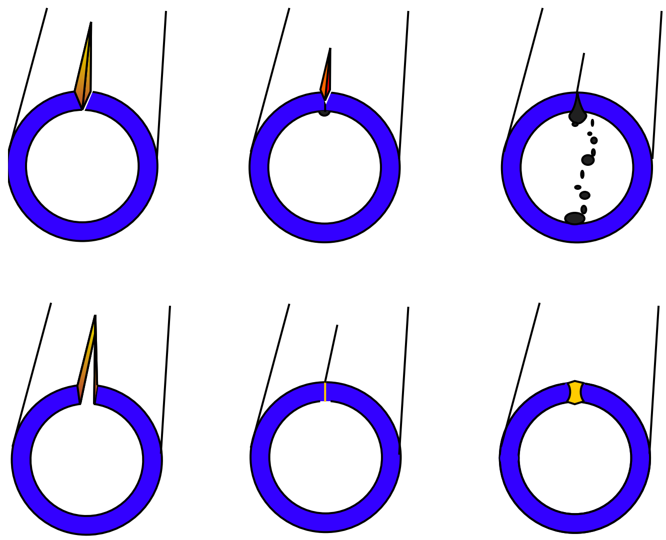
Insufficient cooling can cause ferrite to shatter, and vibration or mechanical shock has a similar effect. Contrary to common believe, the loss of magnetic properties that occurs when ferrite is heated above its Curie point is completely reversable, and the properties revert to normal when the temperature is lowered. If there is no physical damage to the ferrite, its properties are not affected.

Controlling the I.D. bead

The I.D. bead can be minimised by threading the mill so that any slitting burr is on the bottom of the strip. In this way, it ends up on the outside, rather than the inside of the tube.

I.D. bead height can also be adversely affected by improper weld roll adjustment. The rolls should always be set using a plug gauge & then left alone! They should not be used to increase or decrease the amount of weld upset. This should be done by adjusting the fin passes and breakdown passes, or by changing the strip width. There is only one position of the weld rolls that results in a round tube. Using the weld rolls to control the amount of upsetting distorts the tube & will affect the edge presentation.

It is critically important that the edges of the strip are parallel to each other as they enter the weld rolls. The purpose of the fin passes is to "coin" the edges, to establish the correct orientation, but improper adjustment or worn tooling can prevent this from happening. If the strip is not worked sufficiently in the fins, the inside corners will meet first, and the majority of weld current will flow through the point of first contact. In order to get the weld to penetrate through to the outside of the tube, the inside corner has to be overheated to a point where it melts, causing premature impeder failure, a rough I.D. beads, and in extreme cases, "birdshot" inside the tube.



Solid state vs Vacuum tube

Most newer welders use transistors rather than vacuum tubes to generate the high frequency power that feeds the coil. Both types rectify the 3 phase power, then use either vacuum tubes or transistors to chop the direct current into narrow pulses. The pulse stream feeds a resonant tank circuit that converts the pulses into a clean sine wave at the tank's resonant frequency. The main differences in two technologies are in the currents and voltages used.

Vacuum tubes operate at high voltages & low currents. A typical induction welder uses 12,000 to 15,000 volts at 10 to 50 amps. A high frequency transformer reduces this to a lower voltage which is applied to the work coil. A tube mill is not a good enviromnent for high voltage equipment, so vacuum tube welders require more maintenance.

Transistor inverters generally operate off DC power at around 500 volts, so currents are correspondingly much higher. Although the transistors themselves are more efficient & reliable than vacuum tubes, the high currents employed can cause significant losses to occur in buss bars, work coils & the coil connections.

The only true measure of efficiency is to compare input kVA/hours (not kilowatt/hours!) to welded tube produced per hour. Solid state welders should still theorectically come out ahead, but this isn't always the case!

The best frequency

Induction tube welders are available in frequencies as low as 80 kHz., and as high as 800 kHz., as well as a few that are adjustable over a fairly wide range. Higher frequency units offer more versatility, since most of the effects of a lower frequency can be achieved by adjusting coil and/or impeder position. The only significant drawback of too high a frequency is that it results in higher voltages across the work coil, and across the strip edges, both of which can result in arcing.

There is no benefit in using a high frequency (>400kHz.) to weld 8" O.D. x 1/2" wall pipe, and higher frequency welders are more expensive to manufacture. The benefits of higher welder frequencies are mostly apparent in producing tubing below 1" in diameter, where there is very little space for an impeder. An impeder is more effective at higher frequencies, but it also requires more cooling.

There are many solid state welders in service that produce high quality welded tubing below 1" O.D. using frequencies below 200kHz., but they are not as efficient as units operating in the 400kHz range. The difference in efficiency has very little to do with the depth of the heat affected zone, which only varies slightly over this range. The main factors are that a higher frequency improves the ratio of vee current to I.D. current, and makes impeders more effective. It also reduces coil losses because coil currents are lower. A difference of just 10% in the efficiency of a 400kW welder can cost $25,000.00 a year in added power costs.

Stainless & non ferrous alloys.

Most of what has been covered applies to all induction welded tube & pipe, but there are a few special factors to consider when welding Stainless Steels & certain other non ferrous metals.

The "stainless" properties of corrosion resistant steels are due to the fact that the surface is already oxidized! Chromium is an extremely reactive metal that readily oxidizes in the presence of atmospheric oxygen. Chromium oxide is a hard, transparent refractory material which is impervious to most corrosive elements. Unlike iron oxides, which melt at a lower temperature than the base metal, chromium oxide remains a solid, and must be forced out of the weld interface if defects are to be prevented.

Although most chromium oxide is wiped off the metal surface by the fins, it immediately reforms at the elevated temperatures of the weld area. Although atmospheric oxygen is a factor, any water in the weld area is a far greater problem. At weld temperatures, water doesn't just vaporize - it dissociates into its components, oxygen & hydrogen. The monatomic oxygen (O, not O_2) is far more reactive than ordinary oxygen, so chromium oxide reforms immediately on the faying edges of the tube.

It is essential to exclude water & preferably oxygen as well from the weld area when induction welding 300 series (austenitic) stainless. 400 series has little or no chromium, so it is less of a problem. Use of water cooled return flow impeders is a requirement for welding stainless, and a low pressure inert gas atmosphere is sometimes used as well.

Because stainless steels are poor thermal conductors, there is a tendency for the corners of the strip to overheat, and for a layer of molten metal to form on the surface of the faying edges. Use of a lower frequency can help to reduce this, but the same effect can be achieved by moving the impeder back toward the entry end of the mill, or eliminating it altogether. More power is required, but the increase is less than with carbon steel because austenic stainless and other non ferrous materials have a much lower magnetic permeability than ferritic steels. This reduces the need for an impeder.

Aluminum, copper & their alloys also have less need for impeders, however their thermal conductivity is high, so short, closely coupled coils should be used to minimise the loss of weld heat by conduction. Aluminum also readily forms insoluble oxides which must be eliminated from the weld area. Remember that grinding wheels & sandpaper are made of aluminum oxide. This is definitely not a material that you want incuded in the weldment! Although water does not dissociate at the temperatures used to weld aluminum, it causes corrosion if left in the tube so return flow impeders are normally required.

