Complete Guide to Induction Coil Design

Creating the Right Custom Inductor for Your Project

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INDUCTION HEATING SOLUTIONS
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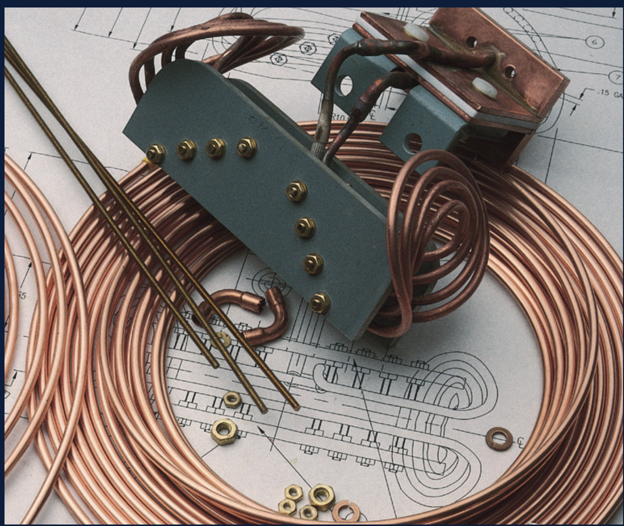

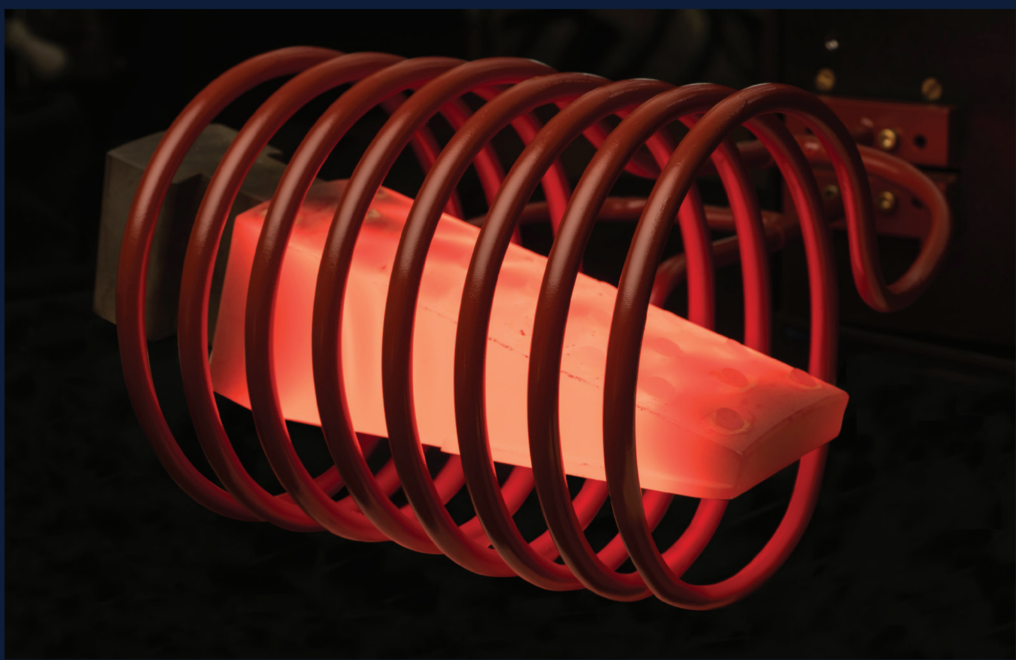

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Table of CONTENTS

SECTION 1: COIL BASICS 4
HOW COILS WORK 4
TRANSFORMER EFFECT 5
COIL BASICS 5

SECTION 2: CHOOSING YOUR COIL TYPE 6
COMMON COIL TYPES 6
COIL EFFICIENCY 11
APPLICATIONS 11

SECTION 3: DESIGNING YOUR COIL 12
DESIGN CONSIDERATIONS 12
TUBING CHOICE 12
NUMBER OF COIL TURNS 14
LEAD DESIGN 14
BRACING OF COILS 17
COUPLING DISTANCE 18
COIL FORMING 19

SECTION 4: CUSTOMIZING YOUR COIL DESIGN FOR HEATING UNIFORMITY, WORKPIECE SHAPE, & PART IRREGULARITY 20
COIL CHARACTERIZATION 20
SIX OTHER COMMON WAYS TO IMPROVE HEATING UNIFORMITY 21
HEATING TWO SEPARATE AREAS ON A PART 22
COUNTER WINDING AND SHORTED TURNS 22
HEATING A PART WITH SECONDARY FABRICATIONS 23
HEATING PARTS WITH TAPERED SHAPES 23
HEATING A VARIETY OF DIFFERENT PARTS WITH ONE COIL 24

SECTION 5: RESOURCES 25
FORMULAE & CALCULATIONS 25
GLOSSARY 26

» Complete Guide to Induction Coil Design

Induction coil design can have a major impact on part quality, process efficiency, and manufacturing costs.

This guide provides (almost) everything you need to design the optimal coil for your part and process.

The first section covers Coil Basics - essentials of how coils work (a.k.a inductors, work coils) and why they're designed the way they are.

The second section outlines different Types of Coils, common applications, and what affects coil efficiency.

The third section provides the details of Designing Your Coil, from the type of tubing to how far away your coil needs to be from your workpiece.

The fourth section covers issues you may face regarding Heating Uniformity & Part Irregularity, plus how to address these issues.

Section five includes calculations you might need and definitions of common induction coil terminology.

If you require additional assistance designing or manufacturing your coil, don't hesitate to contact us.

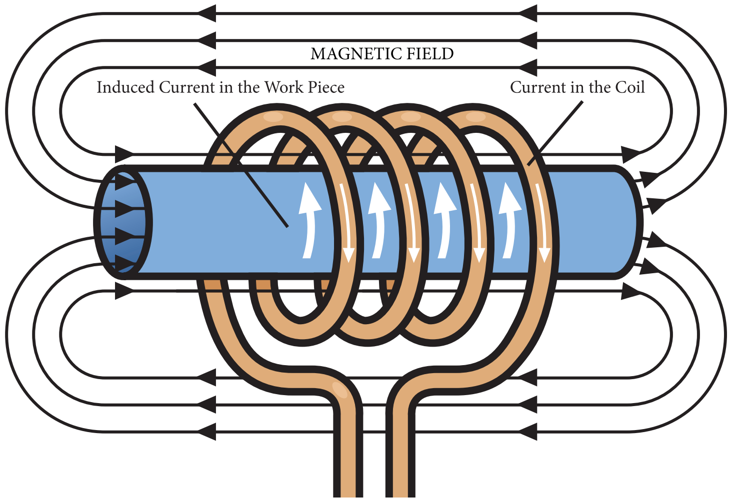
Section 1: Coil Basics

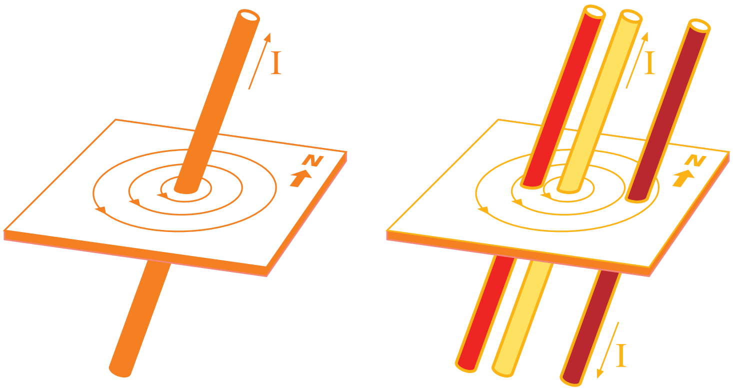
HOW COILS WORK

The induction coil determines how effectively and efficiently a workpiece is heated. Induction coils are water-cooled copper conductors made of copper tubing that is readily formed into the shape of the coil for the induction heating process. Induction heating coils do not themselves get hot as water flows through them. Work coils range in complexity from a simple helical- or solenoid-wound coil (consisting of a number of turns of copper tube wound around a mandrel) to a coil that is precision machined from solid copper and brazed.

Coils transfer energy from the power supply to the workpiece by generating an alternating electromagnetic field due to the alternating current flowing in them. The coil's alternating electromagnetic field (EMF) generates an induced current (eddy current) in the workpiece, which generates heat due to I Squared R losses (core losses).

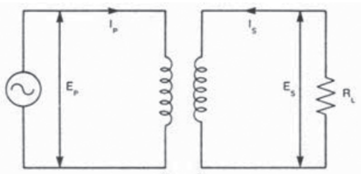
The current in the workpiece is proportional to the coil's EMF strength. This transfer of energy is known as the transformer effect or eddy current effect.





» Section 1: Coil Basics

TRANSFORMERS & INDUCTION COILS



E_p = primary voltage (V); I_p = primary current (A); N_p = number of primary turns; I_s = secondary current (A); N_s = number of secondary turns; E_s = secondary voltage (V); R_l = load resistance(Ω)

Electrical circuit illustrating the analogy between induction heating and the transformer principle.

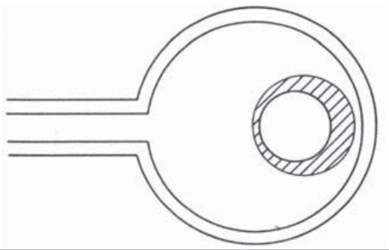
Because coils use the transformer effect, characteristics of transformers can be helpful in understanding coil design. The inductor is similar to a transformer primary, and the workpiece is equivalent to the transformer secondary (assumed to be a single turn).

Two important features of transformers that impact coil design:

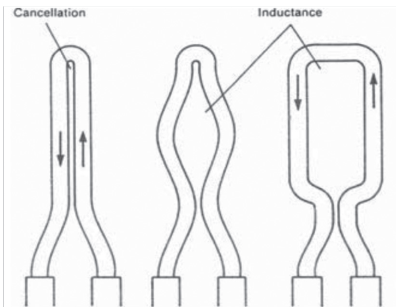
- Efficiency of coupling between the windings is inversely proportional to the square of the distance between them
- (Current in the primary of the transformer * # of primary turns) = (current in the secondary * # of secondary turns)

Because of the above relationships, there are five conditions that should be kept in mind when designing any coil for induction heating:

FIVE BASICS OF COIL FUNCTIONALITY



Induction heating pattern produced in a round bar placed off center in a round induction coil.



Effect of coil design on Inductance (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

1. **Higher flux density near the heating area means a higher current is generated in the part.**

   Coil should be coupled as close to the part as possible, and the largest possible number of magnetic flux lines therefore intersect the workpiece at the heating point. This allows for maximum energy transfer.

2. **The greatest number of flux lines in a solenoid coil are toward the center of the coil.**

   The flux lines are concentrated inside the coil, providing maximum heating rate at that location.

3. **The geometric center of the coil is a weak flux path.**

   Flux is most concentrated closer to the coil turns themselves, and decreases with distance from the turns.

   If a part were placed off center in a coil, the area closer to the coil turns would intersect a greater number of flux lines and thus be heated at a higher rate. The area of the part away from the copper coil experiences less coupling and would be heated at a lower rate.

   This effect is more pronounced in high-frequency induction heating.

4. **The magnetic center of the inductor is not necessarily the geometric center.**

   At the point where the leads and coil join, the magnetic field is weaker.

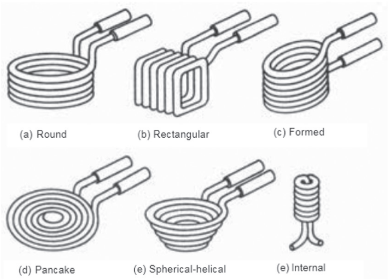
   This effect is most pronounced in single-turn coils. As the number of coil turns increases and the flux from each turn is added to that from the previous turns, this condition becomes less important.

   Due to the impracticality of always centering the part in the work coil, the part should be offset slightly toward this area in static heating applications. If possible, the part should be rotated to provide uniform exposure.

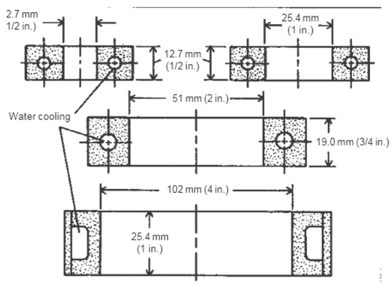
5. **Coil must be designed to prevent cancellation of the magnetic field.**

   If opposite sides of the inductor are too close, the coil does not have sufficient inductance required for efficient heating. Putting a loop in the coil at the center will offset this effect. The coil will then heat a conducting material inserted in the opening.

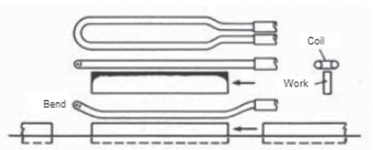
Section 2: Choosing Your Coil Type



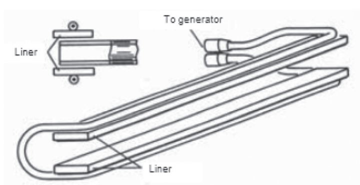
Multiturn coils designed for heating parts of various shapes: (a) round; (b) rectangular; (c) formed; (d) pancake; (e) spiral-helical; (f) internal (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Typical proportions of various single-turn coils (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Typical channel coil used to heat the edges of discrete lengths of rectangular bar stock; end of coil is decoupled by bending to prevent overheating of ends (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Use of a liner on a single-turn channel coil to provide a wider heating pattern on the workpiece (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

THERE ARE MORE THAN 20 DIFFERENT TYPES OF COILS USED FOR INDUCTION HEATING.

Here are their pros and cons, plus some common applications. The helical solenoid coil provides a wide range of heating behaviors since the part or heating area is located within the coil, in the area of greatest magnetic flux.

1. MULTI-TURN HELICAL COIL

The helical (solenoid) is the most common and by far the most efficient coil. The number of turns defines the length of the heating pattern.

The workpiece can be stationary in the coil to provide a defined heating band in “single shot heating.” Or, the workpiece can be moved through the coil to heat a longer part with a highly uniform heating pattern called “scan heating.

2. SINGLE-TURN COIL

Single-turn coils are ideal for heating a narrow band of a workpiece or the tip of a workpiece. These coils can also scan the length of a workpiece and are commonly used for heat treating.

These coils are often tight to the part to provide a precise heat pattern.

3. MULTI-POSITION HELICAL COIL

Multi-position coils are often used to produce more parts in a given time while allowing for the full heating process.

Any number of positions are possible but typically up to 8 positions are practical. Parts can be heated simultaneously or can be indexed in and out of different positions, depending on the heating process required.

4. CHANNEL COIL / CONVEYORS

When power densities are low and heating cycles not extremely short, parts can be processed by use of a turntable or conveyor in a continuous or indexing mode. The coil must then be designed to permit easy entry and exit of the part.

Coils can be formed so the workpiece is heated as it moves through the electromagnetic field by a linear transport mechanism. The coil can be configured to heat all of the part or just a single narrow band on the part.

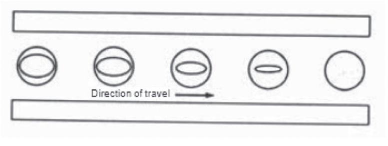
As long as the conveyor material is not electrically conductive, the magnetic field will pass through the conveyor and heat the workpiece as it passes through this field.

The simplest conveyor or channel coil used in these situations is a modification of the hairpin inductor. With the indexing technique, in which the part is at rest in the coil during the heating cycle, the ends of the hairpin can be decoupled to prevent overheating of the ends. These raised portions or bridges also facilitate passage of the part through the coil.

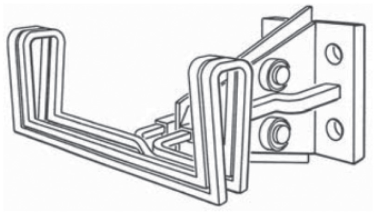
Improving coupling

When a wide heating zone is to be produced on the part, coupling over a greater area can be accomplished through the addition of a liner to the coil turn, or more ampere turns can also be produced with a multiturn channel inductor.

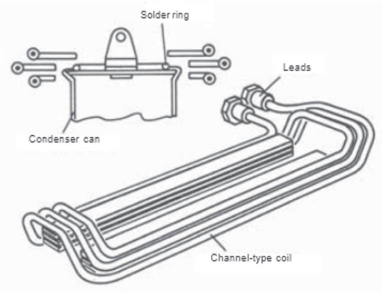
Section 2: Choosing Your Coil Type



Development of the heating pattern in parts moved through a channel coil.



Multiturn channel coil used to increase the ampere turns coupled to an induction heated workpiece (source: Lindberg Cycle-Dyne Inc.)



Multiturn channel coil with a liner added to control the heating pattern (from F.W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950

Channel-coil liners may also be configured to produce specialized heating patterns where greater heat densities are required in specific areas.

Fill factor

During design of heating operations for channel coils, you should consider a "fill factor" for efficiency. The unused portions of the coil appear as lead losses. Parts must be as close as possible without touching to get the full effect of the inductor.

Part rotation

Further, the areas of the workpiece closest to the channel coil receive the greatest portion of flux and heat the fastest.

If conduction through the part is slow, the part should be rotated while passing through the coil. Sufficient time or speed variation must be provided to allow heat uniformity in areas farthest from the coil turns.

5. CURVED CHANNEL COIL

Channel coils are often curved to fit onto a rotary table. They're configured to occupy one of the steps in a multistep assembly process.

6. PANCAKE COIL

Pancake coils are used when it's necessary to heat the workpiece from only one side, or when it's not possible to surround the part. Pancake coils can also be used to heat a small narrow band in the center.

The pancake coil provides a wide range of heating behaviors since the flux from only one surface intersects with the workpiece.

7. SPLIT HELICAL COIL

Single- or multiple-turn split helical coils are used when it's not possible to access the target heating area using a helical coil.

Some applications will require the split-coil design to include the ability to quench through the face of the inductor.

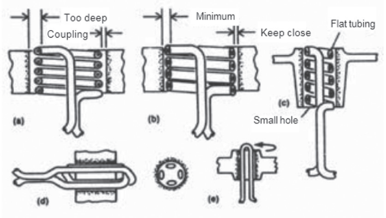
The faces of the hinged and fixed portions of the coil must have good surface-to-surface contact. These are typically faced with silver, or special alloys matched to provide good contact. Clamps are used to ensure closure during heating. High currents pass through this interface at high frequency, which means the life of the contact is generally limited.

Coolant for the coil chamber of the split inductor is carried by flexible hoses that bypass the hinge so that excessive heating does not occur in the movable section during the cycle. The quench chamber is fed by a separate hose arrangement.

The face of the quench chamber is closest to the work during heating, and carries most of the current. It must be sufficiently thick to avoid melting or distortion during the heating cycle.

Split coils often require a means of locating the part in the coil to maintain proper coupling distance. Ceramic pins or buttons are frequently secured to the face of the inductor. These are subject to thermal shock during heating/quenching and should be designed for simple replacement.

Section 2: Choosing Your Coil Type



Induction coils designed for internal (bore) heating (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

8. INTERNAL COIL

The internal coil provides a wide range of heating behaviors for bore heating, where only flux on the outside of the coil is used.

Internal bores can be heated using single- or multiple-turn internal coils. Tubing for internal coils should be made as thin as possible, and the bore should be located as close to the surface of the coil as is feasible.

Because the current in the coil travels on the inside of the inductor, the true coupling of the maximum flux is from the ID of the coil to the bore of the part. Thus, the conductor cross section should be minimal.

	10 kHz	450 kHz
Minimum internal diameter of bore	1.0 in (2.5 cm)	0.44 in (1.1 cm)
Ideal distance between coil OD & part	0.14 in (0.36 cm)	0.062 in (0.16 cm)

The coil tubing can be flattened to reduce the coupling distance, and the coil OD can be increased to reduce the spacing from coil to workpiece.

More turns, or a finer pitch on an internal coil, will also increase the flux density. Accordingly, the space between the turns should be no more than one-half the diameter of the tubing, and the overall height of the coil should not exceed twice its diameter.

If your coil design may produce a pattern of vertical bands, the part should be rotated for uniformity of heating.

Internal coils, of necessity, utilize very small tubing or require restricted cooling paths. Further, due to their comparatively low efficiency, they may need very high generator power to produce shallow heating depths.

9. CONCENTRATOR PLATE COIL

Concentrator plates are used in single- or multiple-turn coils to focus the current and produce a defined heating effect in the workpiece.

These coils may also have a master coil with inserts designed to heat different shaped parts.

10. HAIR-PIN COIL

A long, thin single- or multiple-turn coil is used to heat a long, thin zone on a part. It can also be used to heat a moving web of thin steel or aluminum.

11. ENCAPSULATED COILS

Once the coil is designed and heating pattern proven, it's common to encapsulate the coil. This provides thermal insulation from the process and makes the coil assembly more robust in harsh environments.

Typical encapsulation materials are concrete, ceramics, and epoxy or thermoplastics.

12. TRANSVERSE-FLUX COIL

Used with parts that have a long longitudinal axis and a thin cross-section.

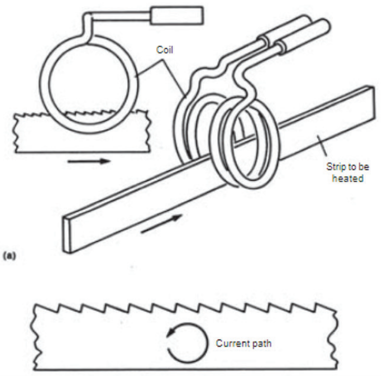


Illustration (a) of one type of transverse coil for heating a thin section; sketch in (b) indicates the current path in the workpiece (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

Section 2: Choosing Your Coil Type

The coil is designed to set up a flux field that is perpendicular to the part. The path of the eddy currents is changed to be parallel to the major axis of the work.

For example, when manufacturing items such as hacksaw blades, the steel moves between the turns of the coil. The eddy-current path is a circular one across the flat of the blade. For heating of wide sheet materials, specially designed transverse-flux inductors are also available.

13. SPLIT-RETURN INDUCTORS

Used when a narrow band of heat is required from one surface only.

The center runner of the work coil carries twice the current of each of the return legs. The pattern on the workpiece produces four times as much heat under the center leg as in each return loop.

With proper balancing, the high-heat path can be extremely narrow, while the heat produced in each return leg will not affect the rest of the part.

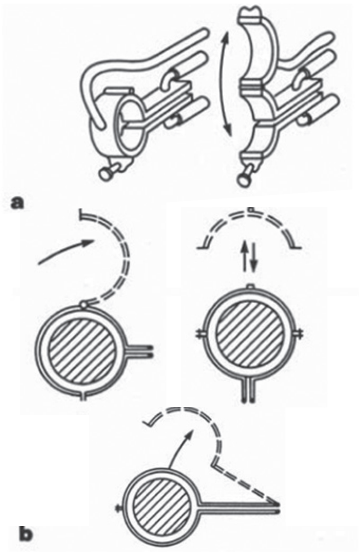
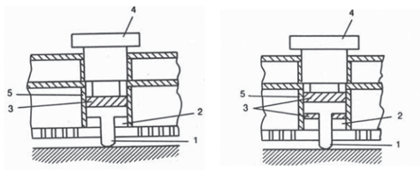
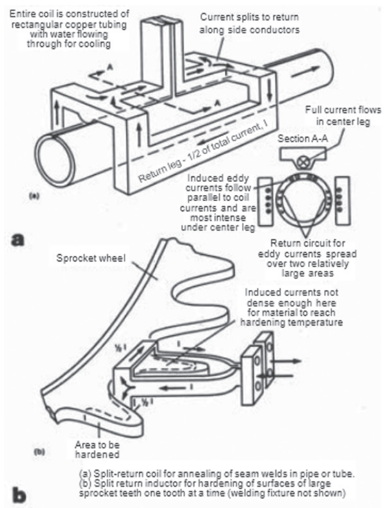


Diagram (a) and schematic illustration (b) of a split inductor used for heating crankshaft journals (from M.G. Lozinski, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969)



Design of metal and ceramic pins for fixing the position of a split inductor on a crankshaft journal (from M.G. Lozinski, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969)



Two types of split-return coils (from C. A. Tudbury, Basics of Induction Heating, Vol. 1, John F. Rider, Inc., New York, 1960)

14. TAPPED COILS

Induction coils can be designed with taps to allow for differences in heated length. For instance, heating "off the end" of a bar, where the heating element must be adjusted to the length.

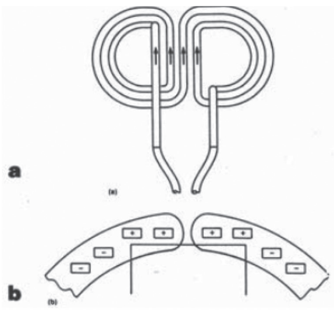
Taps can be brazed to the work coil where a water-cooled strap can be moved from tap to tap. The active portion of the coil will be between the power-supply connection and the tap.

15. BUTTERFLY COILS

For creating an even heating pattern at the end of a bar or shaft.

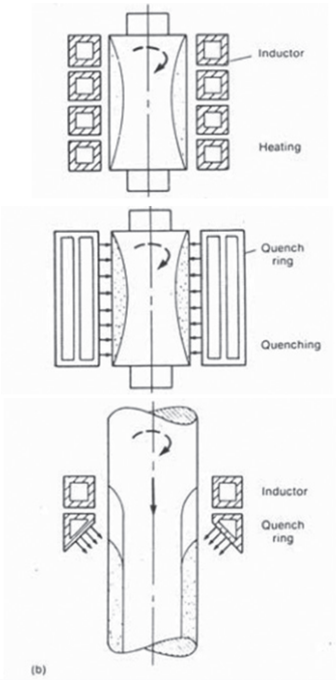
Butterfly coils have two specially formed pancake coils. Center turns must be wound in the same direction so the current paths are additive. Only these center turns should couple directly with the part to produce the desired pattern.

The butterfly "wings" may be bent up to decouple their fields from the shaft, or may be coupled with the shaft itself.

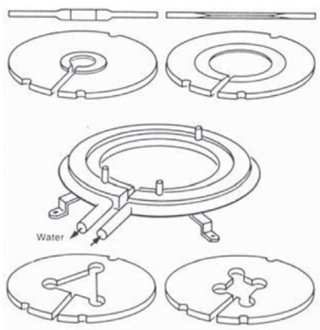


Schematic illustration of a butterfly coil: (a) coil construction (arrows indicate reinforcing type of curent flow in coil); and (b) coupling between the turns of the coil and the end of a bar to produce a uniform heating pattern

» Section 2: Choosing Your Coil Type

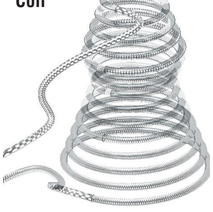


Inductor/quench designs for induction scanning: (a) separate coil and quench; and (b) two-chamber, integral coil and quench (from F.H. Reinke and W. H. Gowan, *Heat Treatment of Metals*, Vol. 5, No. 2, 1978, p. 39)

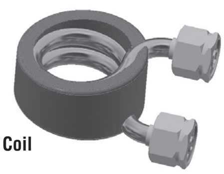


Schematic illustration showing the design of a master coil with changeable inserts (from M.G. Lozinski, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969)

18. Flexible Induction Coil



19. Air Cooled Induction Coil



20. Ferrite Coil

16. COILS FOR INDUCTION SCANNERS

Used for progressive hardening. Built using two methods:

Simple single-turn or multiturn coil with a separate quench ring that can be mounted on the scanner.

For larger production runs, a double chamber coil that incorporates both coil cooling and quenching capabilities is often the preferred choice. Cooling water flows from the inductor chamber to keep copper resistivity low. Quenchant is sprayed from perforations in the beveled face onto the workpiece as it exits.

The beveled face is normally at an angle of 300 to the vertical to allow some soaking time between heating and quenching. This delay helps increase uniformity and reduce fluid runback that can cause uneven heating of the workpiece.

Well-directed quench spray holes are required inasmuch as “barber poling” can occur due to erratic or misdirected quenchant that precools the part ahead of the main quench stream.

17. MASTER WORK COILS AND COIL INSERTS

Used for small batches where a single-turn coil can be used.

Master work coils provide a simple, rapid means of changing coil diameters or shapes to match a variety of parts. Master work coils typically consist of copper tubing that provides both an electrical connection to the power supply and a water-cooled contact surface for connection to a coil insert.

The copper tube is bent into the form of a single-turn coil and soldered to a copper band that conforms to the slope of the coil insert and is recessed.

Read about designing coil inserts here.

18. FLEXIBLE INDUCTION COILS

Used for heating parts like large steel dies, or complex geometry parts, where traditional rigid coils are not practical due to loading and unloading constraints. Coils are then designed with flexible copper conductors located inside flexible non-conducting tubes to be wound on location. Induction powers up to 200-250kW can be used with these coils. Higher powers are possible with careful manipulation of the cooling water paths in the coil designs.

19. AIR COOLED INDUCTION COILS

There are some special instances where water cooling inside induction coils is not practical or required. In these situations, air-cooled copper coils are used for heating. The copper conductors can be constructed with solid copper rods, flexible copper braids, or litz wires. Certain aerospace and medical applications successfully use air cooled coils for heating.

20. COILS WITH FLUX CONTROLLERS

Coils radiate magnetic fields that sometimes heat neighboring metallic fixtures or supports. This can be avoided by wrapping the outside of the induction coil with a ferrite material. The ferrite material captures all the stray magnetic field by offering a low resistance gateway. Since the magnetic field flows through the ferrite there is less tendency to heat surrounding metal pieces.

» Section 2: Choosing Your Coil Type

TYPICAL COUPLING EFFICIENCIES FOR INDUCTION COILS

Frequency	10 Hz		450 kHz	
Type of coil	Magnetic steel	Other metals	Magnetic steel	Other metals
Helical around workpiece	0.75	0.50	0.80	0.60
Pancake	0.35	0.25	0.50	0.30
Hairpin	0.45	0.30	0.60	0.40
One turn around workpiece	0.60	0.40	0.70	0.50
Channel	0.65	0.45	0.70	0.50
Internal	0.40	0.20	0.50	0.25

Coil efficiency is the energy delivered to the coil that is transferred to the workpiece. This is NOT the same as overall system efficiency.

Typically, helical coils used to heat round workpieces have the highest values of coil efficiency. Internal coils have the lowest values.

It is important to note that, with the exception of the pancake and internal coils, the heated part is always in the center of the flux field. Regardless of the part contour, the most efficient coils are essentially modifications of the standard, round coil.

A conveyor or channel coil, for example, can be looked at as a rectangular coil whose ends are bent to form "bridges" in order to permit parts to pass through on a continuous basis. The parts, however, always remain "inside" the channels where the flux is concentrated.

Areas to be hardened are beside the center of the coil turns, and thus are kept in the area of heaviest flux.

INDUCTION COIL APPLICATIONS – WHICH COIL SHAPES ARE TYPICALLY USED?

Heat treating
- Simple solenoid coils (single- & multi-turn)

Hardening
- Multiple position helical coils
- Simple solenoid coils (single- & multi-turn)

Progressive Hardening
- Simple solenoid coils (single- & multi-turn)

Brazing
- Simple solenoid coils (single- & multi-turn)
- Contoured coils to match the shape of the part being heated.
- Channel coils

Soldering
- Simple solenoid coils (single- & multi-turn)
- Contoured coils to match the shape of the part being heated.
- Channel coils

Forging
- Simple solenoid coils (single- & multi-turn)
- Multi position helical coils

Electric Melting

Tempering
- Simple solenoid coils (single- & multi-turn)
- Multi position helical coils
- Internal bore coils for internal diameter heating
- Channel coils

Melting
- Multi turn helical coils, having multiple parallel water and electric paths

Annealing
- Simple solenoid coils (single- & multi-turn)
- Multi position helical coils
- Pancake coils, transverse flux coils
- Channel coils

Shrink-fitting
- Pancake coils, transverse flux coils
- Channel coils

Bonding
- Simple solenoid coils (single- & multi-turn)
- Multi position helical coils
- Pancake coils, transverse flux coils

Curing
- Simple solenoid coils (single- & multi-turn)
- Multi position helical coils
- Pancake coils, transverse flux coils

Section 3: Designing Your Induction Coil

COIL DESIGN CONSIDERATIONS

Coil design is essential to the effectiveness and efficiency of an induction heating process. This is based on a few things:

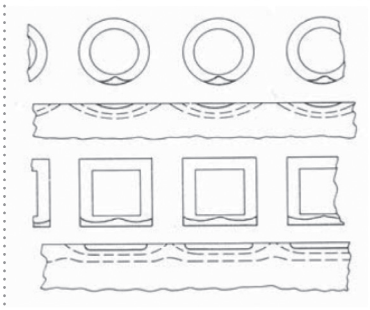
Basic Considerations	
Coil efficiency	Coil efficiency is a measure of the energy transferred to the workpiece off the energy delivered to the coil. This is NOT the same as overall system efficiency.
Heating pattern requirements	The heating pattern is a mirror reflection of the coil shape. The design of the coil is the most important factor for determining the heating pattern.
Part motion relative to coil	Several applications rely on part movement with the help of conveyors, turntables, or robots. A properly designed induction coil incorporates these individual handling requirements without the loss of heating efficiency.
Production rate	If one part is needed every 30 seconds but a 50-second heating time is required, it will be necessary to heat the parts in multiples to meet the desired production rate.
Type of power supply	Solid state components are preferred in the induction heating power supply as opposed to vacuum tube components. Design should be such that it is flexible, versatile and efficient in converting the energy draw from the grid to the heating process.
Frequency	Higher frequencies are used for applications like brazing, soldering, annealing or heat treating, where surface heating is desired. Lower frequencies are preferred for applications requiring through-heating of the parts to the core like forging and die heating.
Powder-density requirements	Higher power densities are required for short cycle heating applications requiring high temperatures. Higher power densities may also be required to keep the hot zone confined to a small area, reducing the heat affected area.
Ferrous vs nonferrous	Ferrous metals heat much more efficiently than non-ferrous metals due to combination of eddy current and hysteretic heating. They are therefore preferred materials to heat with induction. However, they should be avoided in the design of holding fixtures for parts as they may waste energy by heating from the magnetic fields.

Start with understanding where the heat needs to be generated in the part to perform the process, and then design the coil to achieve the heating effect.

Matching the coil to the induction power supply is also essential to the efficiency of the process. Frequency-agile induction systems make it easy to match a wide range of coils with a multi-tap output transformer in the power supply.

In addition, material-handling techniques determine what type of coil is needed. If a part will be inserted in a coil, moved on a conveyor, pushed end to end, or if the coil/heat station will move onto the part, the chosen coil design must accommodate these movements.

SELECTION OF TUBING



Comparative heating patterns produced by using round vs. square tubing for a solenoid induction coil (from M. G. Lozinsky, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969)

Because of its low resistivity, fully annealed, high-conductivity copper is most commonly used for induction heating coils.

- The copper is typically in a tubular form, with a minimum outer diameter of 0.125 in (0.32 cm) to allow for water cooling. Diameters can be as large as 2 in (5.1 cm) for high power applications.
- Material of this kind is available in a wide range of cross-sections (round, square, and rectangular) and sizes.

In addition to the I squared R loss due to its own resistivity, the coil surrounding the heated part may absorb additional heat through radiation and/or convection.

Therefore, it is essential that the tubing selected for the work coil have a sufficient cooling capacity to remove this heat. Otherwise, the resistivity of the copper will increase due to the temperature increase, thus creating greater coil losses.

In some instances, such as large coils, it may be necessary to break up the individual water paths in a coil to prevent overheating and possible coil failure.

Another factor in the selection of tubing for induction coils relates to the fact that the current in the workcoils is traveling at a specific reference depth that depends on the power-supply frequency and the resistivity of the copper.

Accordingly, the wall thickness of the coil tubing should be selected to reference-depth limits similar to those used for induction heating of copper. However, copper availability must be considered, and often wall thicknesses less than twice the reference depth are used with only a nominal loss in overall coil efficiency.

Selecting copper tubing wall thickness for induction coils:

Frequency	Theoretical wall thickness (= 2 * reference depth (a)), mm (in.)	Typical wall thickness available, mm (in.)	Minimum tube diameter (b), mm (in.)
60 Hz	16.80 (0.662)	14.00 (0.550)	42.00 (1.6550)
1800 Hz	9.700 (0.382)	8.130 (0.320)	24.30 (0.9550)
540 Hz	5.590 (0.220)	4.670 (0.184)	14.00 (0.5500)
1 kHz	4.110 (0.162)	3.430 (0.135)	10.30 (0.4050)
3 kHz	2.390 (0.094)	1.980 (0.078)	5.970 (0.2350)
10 kHz	1.320 (0.052)	1.070 (0.042)	3.300 (0.1300)
450 kHz	0.150 (0.006)	0.890 (0.035)	0.380 (0.0150)
1 MHz	0.080 (0.003)	0.890 (0.035)	0.190 (0.0075)

(a) Resistivity of copper assumed to be 1.67 * 10^{-6} • cm (0.66 * 10^{-6} • in.).
(b) Tube ID requirements for adequate cooling-water flow should also be considered.

Square tubing

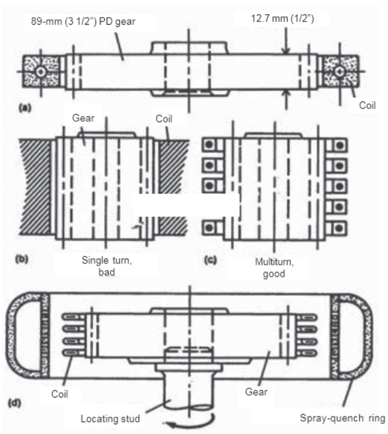
Square copper tubing is also commercially available and is frequently used in coil fabrication.

- Offers a considerable advantage in that it couples more flux to the part per turn than round tubing for tightly coupled coils
- More easily fabricated - it will not collapse as readily on bending
- Easily mitered to create sharp, close bends as required

If only round tubing is available, it can be flattened in a vise or other simple device to adjust the resultant thickness dimension. This flattening can be done with minimal decrease in dimension of the water-flow path.

Section 3: Designing Your Induction Coil

NUMBER OF COIL TURNS



Selection of single-turn vs. multiturn coils depending on the length-to-diameter ration of the workpiece (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

Multiturn coils

In multiturn coils, as the heated length increases, the number of turns generally should increase in proportion. Multiturn coils of this type are generally utilized for large-diameter, single-shot heating.

When the length of the coil exceeds 4-8x its diameter, uniform heating at high power densities becomes difficult. In these instances, single-turn or multiturn coils that scan the length of the workpiece are often preferred.

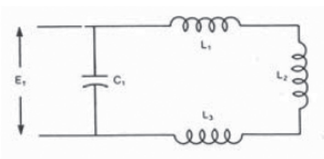
Multiturn coils generally improve the efficiency, and therefore the scanning rate, when a power source of a given rating is used.

Single-turn coils

Single-turn coils are also effective for heating bands that are narrow with respect to the part diameter.

The relationship between diameter and optimum height of a single-turn coil varies somewhat with size. A small coil can be made with a height equal to its diameter because the current is concentrated in a comparatively small area. With a larger coil, the height should not exceed **one-half the diameter.**

LEAD DESIGN



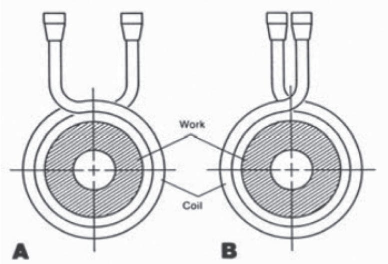
Schematic circuit diagram indicating the inductance of the coil leads and induction coil itself: L_1, L_3-lead inductances; L_2-induction-coil inductance; C_1-tank capacitance; E_1-tank voltage

All coils represent an inductance to the tank circuit. However, in practice, the working portion of the coil may be only a small portion of the inductance presented to the tank. There may be a considerable distance of output lead between the output terminals of the generator and the heating portion of the work coil.

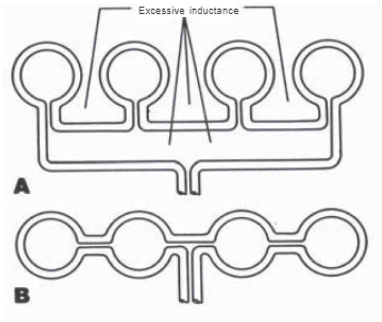
Design and construction of these work-coil leads can be a major factor in determining job feasibility. The effect of lead construction on system performance can be best understood with respect to its tank circuit.

1. **Each lead connecting the tank capacitor to the coil has its own inductance.**
2. **The full voltage will never appear across the work coil.**
   a. If voltage is impressed across the total number of inductances, then some voltage drop appears across each.
   b. If the inductance of the coil is approximately 10 times the total inductance of the leads or greater, a maximum of 10% of the total voltage will be lost in the leads. Any loss less than this can be considered nominal.
3. **Higher inductance in the coil heating area offsets the effect of lead inductance.**
   a. Some coils have many turns, a large cross-sectional area, and thus fairly high inductance. Hence, the comparative lead inductance is small.
4. **As the distance between the heat station and coil increases, lead inductances become more noticeable.**
   a. As the frequency increases, coils often become smaller in size, and their inductance and inductive reactance decrease.

Section 3: Designing Your Induction Coil



Effect of coil-lead spacing on lead inductance; closer spacing, as in (b), reduces lead inductance and thus power losses (from F.W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Lead construction for multiplace inductors; lead design in (b) is preferable because of lower heat inductance (from F.W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

b. With leads far apart, the space between the leads presents an inductance which may be almost equal to or larger than that of the coil. Thus, a major portion of the voltage will not appear on the coil.

c. A better design minimizes this gap and thus improves heating efficiency.

5. Leads can interact with nearby metal structures.

a. Because all leads have some inductance, they can act as work coils. Thus, a conductor placed within their field will be heated. Leads placed adjacent to metal structures will tend to heat them.

b. In addition to unwanted heat, this loss reduces the power available to the load.

c. It is important that lead-to-lead separation be minimized and proximity to metallic structural members be considered. Whenever possible, duct housings, trays, or conduits must be of low-resistivity or insulating materials, such as aluminum or plastic.

Fishtail

Induction heating lead designs typically make use of water-cooled copper plates or tubes. When coil voltages are low (X800v), a low-inductance structure known as a fishtail is often utilized.

A fishtail is a pair of copper plates, placed with their wide bus faces parallel, that are water cooled to maintain low resistivity. They're either separated physically with air as an insulator or held together by nylon bolts and nuts, with teflon or a similar material acting as a spacer.

Fishtails extend from the heat station to a point as close as possible to the operating area of the work coil. They present minimum inductance and provide maximum power at the coil.

- Depending on conditions and construction, efficient runs from a few inches up to 15 feet are practical.
- The thickness of the copper plates should be consistent with the frequency (see: suggested wall thickness above)
- Cooling-water paths and sizes must be consistent with the power being transmitted
- The copper plates should increase in width with generator power and the distance of the run
- They should be spaced as close together as possible, with only enough space for proper insulation to prevent arcing. However, good practice still dictates that coil leads be kept to a minimum length
- Copper tubing sizes be consistent with frequency, current, and cooling requirements
- As the coil inductance increases (e.g., as the number of turns or the coil diameter increases), lead length becomes less critical, and plain copper tubing leads then become more practical.

However, larger coils also require higher terminal voltages.

Rigid leads

Rigid leads (tubing or bus) built to the above guidelines are inherently more effective than flexible, water-cooled cable. In some cases, however, it is absolutely necessary to use flexible connections.

Flexible leads

There are several variations in flexible leads, but it must be kept in mind that the inductive lead losses in flexible cables are usually much greater than those for rigid connections.

The most common flexible lead is generally used in applications similar to tilt-type induction melting furnaces and consists of a water-cooled, spiral-wound inner conductor (similar to BX cable, but made of copper) with an outer insulating covering. These leads are used in pairs with one for each lead connection.

Not only must they be sized for current and frequency, but the insulation must be capable of handling the voltage rating of the system. Flexible leads should be tied together with insulating straps.

Coaxial leads

Coaxial leads are also available and may be rigid or flexible. They consist of an inner conductor and an outer sheath or housing that is also used as the return conductor. This outer sheath is generally at ground potential.

In addition to providing an extremely low-inductance lead, the outer ground acts to eliminate possible strong radiation or inductive coupling to adjacent structures.

Rigid coaxial lead is generally quite expensive and is usually limited to those applications where it is imperative to transmit high power at high frequency over some distance.

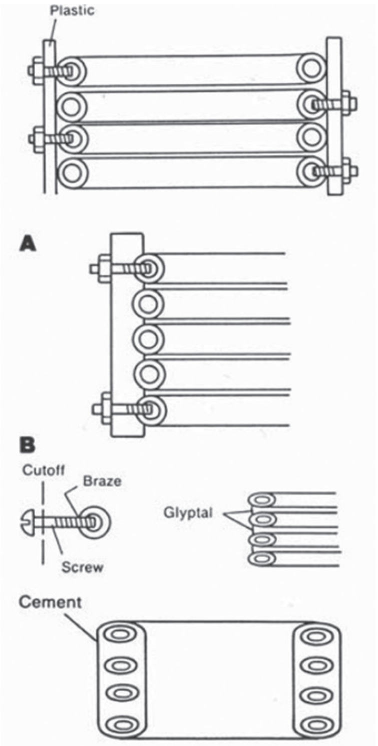
Another type of coaxial cable is the water-cooled type generally used at radio frequencies. It consists of a low-inductance, braided inner conductor that runs through a water-cooled tube, and an outer return braid that is also water-cooled.

This construction is generally utilized with medium-to-high-inductance coils because its construction does not greatly minimize lead inductance but does provide flexibility.

This last type of lead is most common when the operator must physically move the coil from part to part as is the case with bottle sealing.

» Section 3: Designing Your Induction Coil

BRACING COILS



Typical techniques for bracing of induction-coil turns (from F.W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

Electric currents flow in both the workpiece and the coil, which develops magnetomotive forces between the two. These forces can cause undesirable movement during induction heating. The magnitudes of the forces depend on the magnitudes of the currents.

- Coil turns can move relative to each other. Turns must be suitably braced to prevent movement and possible turn-to-turn shorting.
- Coils can move relative to the workpiece, and the part can move in the coil. Coils should not move relative to the part to avoid undesirable changes in the heating pattern, eliminate coil vibration, and reduce acoustic noise.

If proper bracing is not provided, the coil may gradually work harden and finally fail.

TYPICAL BRACING TECHNIQUES

Brass studs

1. Brass studs are brazed to every other turn.

2. These studs are then secured to insulator posts to hold them in a fixed relation to each other.

3. Nuts on each side of the stud at the insulator allow adjustment for characterization of the heating pattern.

Insulation

1. Insulation contoured to hold the turns relative to each other after the end turns are secured with studs.

The insulation used for bracing applications must meet the criteria for the coil design.

In addition to the installation being capable of withstanding the heat radiated from the workpiece, its electrical capabilities must permit it to withstand the voltage between the mounting studs or the turn-to-turn voltages of the coil.

This is of particular concern when using high-voltage RF coils where up to 12,000v may be impressed across the total coil.

a. It may be necessary in these instances to provide slots between the stud locations in the insulator boards to increase the electrical creepage path between the studs.

b. It may also be necessary to increase the heat-resistant characteristics of the insulation by facing the area exposed to the heated surface with a sheet of high-temperature insulation.

Encapsulation

For purposes of rigidity, cleanness, and protection, it is sometimes desirable to encapsulate work coils in a plastic or refractory material. The same kind of care with respect to voltage and temperature characteristics must be taken with these materials as with insulating boards.

- **Epoxy -** For low-temperature induction heating applications, epoxy encapsulation of the coil is quite common.

- **Refractory cement -** For heating steel billets, coils are usually cast in a refractory cement to prevent scale from the part from falling between the turns.

In coating of coils with refractory materials, care must be taken to match the pH of the refractory to that of the material being heated; for example, an acidic refractory is required for the ferrous scale that drops off during high-temperature heating of steels.

COUPLING DISTANCE

THREE MAIN FACTORS:

1. Type of Heating

2. Type of Material (ferrous vs nonferrous)

3. Type of Frequency & Handling

Type of Heating

In static surface heating, in which the part can be rotated but is not moved through the coil, a coupling distance of 0.060 inch (0.15 cm) from part to coil is recommended.

For progressive heating or scanning, a coupling distance of 0.075 inch (0.19 cm) is usually necessary to allow for variations in workpiece straightness.

A fine-pitch, multiturn coil closely coupled to the workpiece develops a very uniform heating pattern.

Similar uniformity can be achieved by opening up the coupling between the part and the coil so that the magnetic flux pattern intersecting the heated area is more uniform. However, this also decreases energy transfer.

Where low heating rates are required, as in through heating for forging, this is acceptable.

When high heating rates are needed, it’s best to maintain close coupling. The pitch of the coil should be opened to prevent overloading of the generator.

Type of Material

For through heating of magnetic materials, multiturn inductors and slow power transfer are utilized. Coupling distances can be looser in these cases — on the order of 0.25 to 0.38 inch (0.64 to 0.95 cm).

Type of Frequency & Handling

It is important to remember, however, that process conditions and handling dictate coupling. If parts are not straight, coupling must decrease.

At high frequencies, coil currents are lower and coupling must be increased. With low and medium frequencies, coil currents are considerably higher and decreased coupling can provide mechanical handling advantages.

In general, where automated systems are used, coil coupling should be looser. The coupling distances given above are primarily for heat treating applications in which close coupling is required.

Section 3: Designing Your Induction Coil

In most cases, the distance increases with the diameter of the part, typical values being 0.75, 1.25, and 1.75 inches (19, 32 and 44 mm) or billet-stock diameters of approximately 1.5, 4 and 6 inches (38, 102, and 152 mm), respectively.

COIL FORMING

In fabrication of copper coils, it must be noted that the copper work hardens with increasing deformation. Thus, most fabricators anneal the tubing every few bends to relieve this condition by heating the tubing until it is bright red, then cooling it rapidly in water. These intermediate anneals prevent fracture of the tubing during fabrication.

In some forming operations, it may be desirable to fill the coil with sand or salt to preclude collapse of the tubing.

In addition, there are several low-temperature alloys - with melting points below 212°F (100°C) - that are normally used to perform this same function.

When the coil is completed, it is immersed in boiling water. The alloy then flows out freely and can be reused at another time.

With any of these techniques, once filled, the tubing acts as a solid rod during forming and can be simply cleared on completion.

Section 4: Customizing Your Coil Design

for Heating Uniformity, Workpiece Shape, & Part Irregularity

Magnetic flux tends to concentrate toward the center of the length of a solenoid work coil. This means the heating rate produced in this area is generally greater than that produced toward the ends.

Further, if the part being heated is long, conduction and radiation remove heat from the ends at a greater rate. The coil can be modified to provide better heating uniformity along the part length.

1. Coil characterization

2. Six other common ways to improve heating uniformity

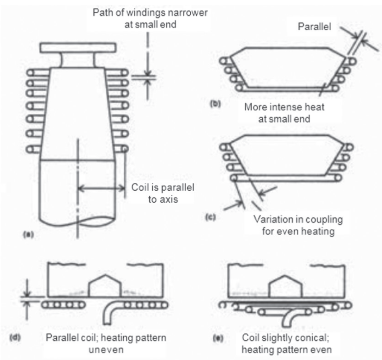
3. Heating two separate areas on a part

4. Heating tapered parts

5. Heating a part with secondary fabrications

6. Heating a variety of different parts with one coil

COIL CHARACTERIZATION



Adjustment ("characterization") of induction heating patterns for several parts by varying the coupling distance or turn spacing (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

The technique of adjusting the coil turns, spacing, or coupling with the workpiece to achieve a uniform heating pattern is sometimes known as "characterizing" the coil.

With all coils, flux patterns are affected by changes in the cross-section or mass of the part. There are several ways to modify the flux field.

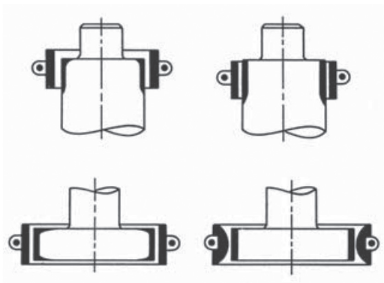
1. The coil can be decoupled in its center, increasing the distance from the part and reducing the flux in this area.

2. The number of turns in the center (turn density) can be reduced.

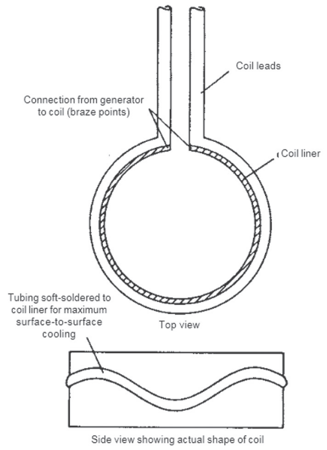
3. Altering a solid single-turn inductor by increasing its bore diameter at the center.

Section 4: Customizing Your Coil Design
for Heating Uniformity, Workpiece Shape, & Part Irregularity

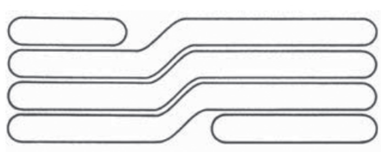
SIX OTHER COMMON WAYS TO IMPROVE HEATING UNIFORMITY



Effect of coil placement on the heating pattern at the end of a workpiece (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Method of inserting a liner in a coil to widen the flux path



Induction coil with an offset (step) used to provide heating uniformity

1. Part rotation

Barber poling occurs when the high flux field adjacent to the coil turns produces a spiral pattern on the part.

To eliminate barber poling, rotate the workpiece during heating. For most short-duration hardening operations, rotational speeds producing at least 10 revolutions during the heating cycle are ideal.

2. Tapered coil

When the coil extends over the end of a shaft-like part, a deeper pattern is produced on the end. To reduce this effect, the coil must be brought to a point even with or slightly lower than the end of the shaft.

3. Shortened coil

The same condition exists in heating of a disk or a wheel. The depth of heating will be greater at the ends than in the middle if the coil overlaps the part.

The coil can be shortened, or the diameter at the ends of the coil can be made greater than at the middle, thereby reducing the coupling at the former location.

4. Coil liners

A coil liner is a sheet of copper soldered or brazed to the inside face of the coil. This liner expands the area over which the current travels. Thus, a wide field per turn can be created. The height of this field can be modified to suit the application by controlling the dimensions of the liner.

When a liner is used, the current path from the power supply passes through the connecting tubing. Between the two connections, the tubing is used solely for conduction cooling of the liner.

In fabricating coils with liners, it is necessary only to tack-braze the tubing to the liner at the first and last connection points, with further tacks being used solely for mechanical strength.

The remainder of the common surfaces between tubing and liner can then be filled with a low temperature solder for maximum heat conduction, because the coil-water temperature will never exceed the boiling point of water, which is well below the flow point of the solder.

This may be necessary because the copper may be unable to conduct heat fast enough from the inside of the coil.

5. Stepping the coil

Stepping is easily accomplished by annealing the coil after winding and pressing it between two boards in a vise.

6. Flattened tubing

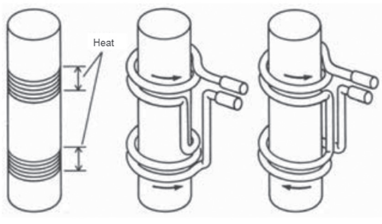
Flattened tubing should be placed so that its larger dimension is adjacent to the workpiece. The stepping of coil turns provides an even, horizontal heating pattern.

Section 4: Customizing Your Coil Design

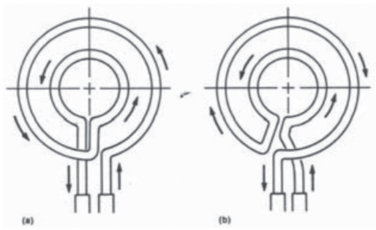
for Heating Uniformity, Workpiece Shape, & Part Irregularity

HEATING TWO SEPARATE AREAS ON A PART

When two separate regions of a workpiece are to be heated, but are close together, it's possible that the magnetic fields of adjacent coil turns will overlap, causing the entire bar to be heated.



Control of heating patterns in two different regions of a workpiece by winding the turns in opposite directions (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Design of pancake coils to provide (a) uniform, or overall, heating or (b) peripheral heating only (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

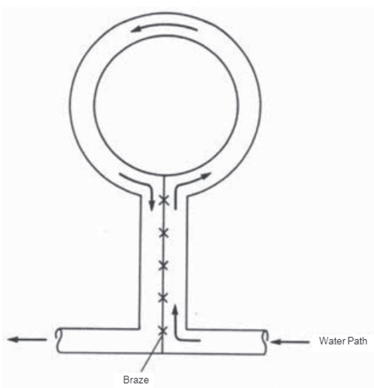
COUNTER WINDING

To avoid this problem, successive turns can be wound in opposite directions. By this means, the intermediate fields will cancel, and the fields that remain will be restricted.

It should be noted that lead placement is critical. Having the return inductor spaced far from the coil leads would add unneeded losses to the system.

A counter wound coil can be used effectively in an application in which the rim of a container is to be heated while the center remains relatively cool.

SHORTED TURNS ("ROBBERS")



Typical construction of a water-cooled flux robber.

Another technique that can be utilized in the above circumstances involves the construction of a shorted turn or "robber" placed between the active coil turns.

In this case, the shorted loop acts as an easy alternative path for concentration of the excess flux, absorbing the stray field. It is therefore sometimes called a flux diverter. As for the active coil turns, the robber must be water cooled to dissipate its own heat.

Shorted coil turns are also used effectively to prevent stray-field heating on very large coils where the end flux field might heat structural frames.

Flux robbers or flux diverters can also be used in fabricating test coils when it is desired to determine the optimum number of turns empirically. In these situations, a few additional turns are provided that can be added or removed as required. These can be shorted with a copper strap or temporarily brazed while tests are made and removed pending the outcome of the heating trials.

Section 4: Customizing Your Coil Design

for Heating Uniformity, Workpiece Shape, & Part Irregularity

PARTS WITH FABRICATIONS

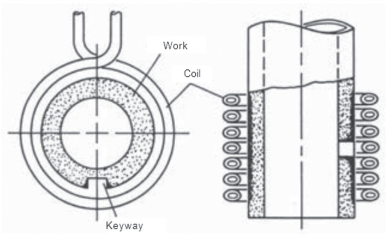
Just as flux tends to couple heat to a greater depth at the end of a shaft, it will do the same at holes, long slots, or projections. If the part contains a circular hole, an additional eddy-current path is produced that will cause heating at a rate considerably higher than that in the rest of the part.

The addition of a copper slug to the hole can effectively correct or eliminate this problem:

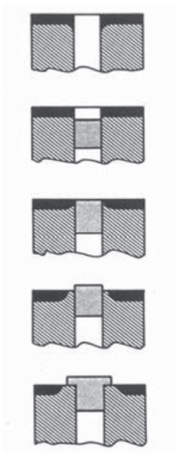
- The position of the slug can control the resultant heating pattern.
- The slug will minimize hole distortion if the part must be quenched following heating.

For slotted parts heated with solenoid coils, the continuous current path is interrupted by the slot, and the current must then travel on the inside of the part to provide a closed circuit. This is the basis for concentrator coils.

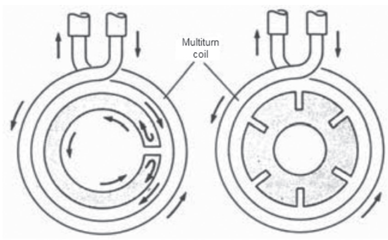
Fun Fact:
With the slot closed, the applied voltage of the work coil causes a higher current to flow. This is due to the fact that the resistive path, now around the periphery of the part, is considerably shorter. The increase in current then produces a considerably higher heating rate with the same coil.



Localized overheating of sharp corners, keyways, and holes most prevalent in high frequency induction heating (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)



Control of the heating pattern at a hole through use of copper slugs (from M.G. Lozinski, *Industrial Applications of Induction Heating,* Pergamon Press, London, 1969)



Localized overheating of slots in certain parts that results from the tendency for induced currents to follow the part contour (from F. W. Curtis, *High Frequency Induction Heating*, McGraw-Hill, New York, 1950)

HEATING PARTS WITH TAPERED SHAPES

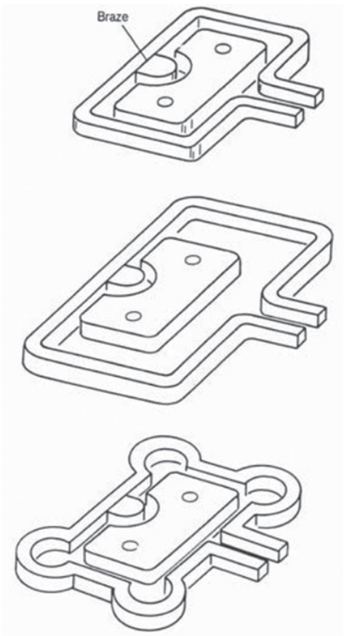
Coil turns can be modified to produce an even heating pattern on a tapered shaft. The closer turn spacing toward the end compensates for the decrease in coupling caused by the taper. This technique also permits “through the coil” loading or unloading to facilitate fixturing.

For instance, a bevel gear with a greater part taper may benefit from a spiral-helical coil.

With a pancake coil, decoupling of the center turns provides a similar approach for uniformity.

» Section 4: Customizing Your Coil Design
for Heating Uniformity, Workpiece Shape, & Part Irregularity

HEATING A VARIETY OF PARTS



Inductor with a relief designed for the hardening of the lateral surface of a template (from M.G. Lozinski, *Industrial Applications of Induction Heating*, Pergamon Press, London, 1969)

Master Coil & Coil Inserts

Inserts clamp to the master coil via matching tapped holes. Inserts are machined from copper with a thickness that matches the required heating pattern. This should be somewhat greater in thickness than the depth of the recess for easy removal.

Because of less-than-optimal cooling, coil inserts are particularly well adapted to short heating times or processes in which they are also cooled by the quenching medium.

Coil insert designs should indicate softening of sharp corners during machining. Corners tend to overheat relative to the rest of the pattern, generating more heat in these locations. Relieving or decoupling of only the corners is the best solution, particularly when a solid inductor is used and the relief can be machined as required.

Section 5: Resources

FORMULAE & CALCULATIONS

- **Coupling distance**

Generally, distance increases with the diameter of the part, typical values being 0.75, 1.25, and 1.75 inches (19,32 and 44 mm) or billet-stock diameters of approximately 1.5, 4 and 6 inches (38, 102, and 152 mm), respectively.

When the length of the coil exceeds 4-8x its diameter, uniform heating at high power densities becomes difficult. In these instances, single-turn or multiturn coils that scan the length of the workpiece are often preferable.

- **Coupling efficiency**

Efficiency of coupling between the windings is inversely proportional to the square of distance between them.

- **Minimum tubing OD**

Minimum outer diameter of copper tubing is 0.125 in (0.32 cm) to allow for water cooling.

- **Rotational speed**

For most hardening operations, which are of short duration, rotational speeds producing AT LEAST 10 revolutions during the heating cycle should be used.

- **Current**

(Current in the primary of the transformer * # of primary turns) = (current in the secondary * # of secondary turns)

- **Voltage loss**

If the inductance of the coil (L2) is approximately 10 times the total inductance of the leads (L1 plus L3) or greater, a maximum of 10% of the total voltage will be lost in the leads.

Any loss less than this can be considered nominal.

- **Lead spacing for internal coils**

More turns, or a finer pitch on an internal coil, will also increase the flux density. Accordingly, the space between the turns should be no more than one-half the diameter of the tubing, and the overall height of the coil should not exceed twice its diameter.

- **Internal coil ID**

For all practical purposes, a bore with a 0.44-inch (1.1-cm) internal diameter is the smallest that can be heated with a 450-kHz power supply.

At 10 kHz, the practical minimum ID is 1.0 inch (2.5-cm).

Excerpts in this guide used with permission from Stanley Zinn.

Section 5: Resources

GLOSSARY

- **Leads**

Sections of coil between the generator and the heating portion of the work coil. Leads carry inductance to the heating portion of the coil, but do not typically interact with the workpiece.

- **Coupling**

The transfer of energy that occurs in the space between the heating portion of the coil and the workpiece.

- **Tubing**

The material through which the electrical current will travel. Also provides the path for water cooling.

- **Generator / capacitor**

The external source of inductance. The work coil is connected to the generator via output terminals that transfer the current into the coil.

- **Water cooling**

Induction heating requires water cooling throughout the system to maintain low resistivity and keep the temperature output in the desired range. Water cooling is different from quenching, where water is sprayed onto the workpiece to bring its temperature down quickly.

- **Heating patterns**

The pattern of heat transferred to the workpiece from heating portions of the work coil. The heating pattern is the mirror image of the coil.

- **Flux**

The amount of heat transferred from the work coil to the workpiece.

- **Inductance**

The ability of the heating system to induce voltage via a varying current and magnetic field.

- **Pitch**

Spacing between centers of neighboring turns; the gap between the turns plus wire diameter.

- **Bore**

Internal surface of a component that requires special work coil design to heat.

- **Turns**

Number of times the coil tubing is wound around a central point.

- **Magnetic field / EMF**

A current flowing in a conductor creates a magnetic field. The field generates a current in the workpiece that's a mirror image of the current in the work coil. The current in the workpiece is proportional to the field strength.

- **Transformer**

The transformer effect says the amount of current induced in the workpiece is proportional to the number of turns on the coil and is generated as a mirror image of the work coil.

- **Hysteretic heating**

Comes into effect when the workpiece is a magnetic material such as carbon steel.

Energy is generated within the workpiece by the alternating magnetic field, which changes the magnetic polarity within the workpiece.

Hysteretic heating occurs in the workpiece only up to the Curie temperature (750° C for steel) when the material's magnetic permeability decreases to 1.

About Ambrell

Founded in 1986, Ambrell Corporation, an inTEST Company, is a global leader in the induction heating market. We are renowned for our application knowledge and engineering expertise. In addition, our exceptional product quality and outstanding service and support are at the core of our commitment to provide a superior customer experience.

We are headquartered in the United States with additional operations in Europe including the United Kingdom and the Netherlands. All Ambrell products are designed, engineered and built at our manufacturing plant in the United States, which is an ISO 9001-certified facility. Over the last three decades we have expanded our global reach through an extensive distribution and OEM network, and today we have more than 15,000 systems installed in over 50 countries.

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