# Enhancing Induction Heating Processes by Applying Magnetic Flux Controllers

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## Abstract

The use of magnetic flux controllers is one of the most effective methods for the improvement of induction heat treating systems. The proper application of the magnetic flux controllers provides work coil efficiency improvement, better utilization of the energy transferred into the part and excellent heat pattern control. Faster heating results in less part distortion from lower total heat in the part, better metallurgical properties and higher production rates. Power Inductors$^{TM}$ are state-of-the-art induction coils equipped with magnetic flux controllers or concentrators made from Fluxtrol® or Ferrotron® magnetodielectric materials. These materials are composites produced from soft magnetic powder and binder pressed and heat treated according to a special technology. Fluxtrol and Ferrotron can be netshaped or machined to any size and shape to suit the requirements of coil geometry and part profile. They can also be used as constructive materials in the coil assembly. For example, quenching media can be supplied to the heated surface through the channels and holes in a magnetodielectric controller. This presentation contains a profound computer simulation study on the use of magnetic flux controllers in an oval static induction heating application. The presentation is addressed to and will be beneficial for all OEM and users of induction heat treating equipment and processes and provides information on advanced induction coil and process design.

## Introduction

The induction heating technique has several inherent advantages. Induction heating generates internal heat sources. These sources can provide high available power densities and high selectivity of heating in the depth and along the surface, which is very important for local heat treating. In addition, induction heating can also work in any processing atmosphere (air, protective gas, vacuum) and has very low stand-by losses.

These physical and technical features give the following technological and economical advantages to the customer:

- Short heating cycles, and high production rates
- Better metallurgical results (hardness, strength, ductility)
- Good control and high repeatability of the process.
- Small or negligible surface oxidation and decarburization due to faster heating
- Low distortion due to localized heating in depth and along the surface
- Reduced energy and labor costs
- Very short start-up times
- More simple and economical steels and quenching media (water or polymer instead of oil for example) may often be used with the same final properties obtained in the parts
- The process is very friendly to the industrial environment (no exhaust gases and other emissions, small size of equipment with high reliability, good automation ability)

The induction heating technique has recently seen many technological breakthroughs in power supplies, computer simulation tools, control and measuring systems and other components. These changes have not been followed by essential improvements in the most critical components of the installation - work coils. And it is not because the work coils are perfect and nothing may be improved in their design. On the contrary, the coils are the least efficient and reliable elements of the whole installation. In the meantime, the development of the methods and programs for mathematical simulation of induction heating systems, new materials for magnetic flux control and technologies constitute a good base for coil and process improvement. The work coil design and manufacturing technology define essentially the workpiece heating quality, installation efficiency and reliability.

The Centre for Induction Technology has developed a procedure for designing induction work coils called Power Inductor Technology$^{TM}$. This state-of-the-art technology is based on the following four principles:

1. Detailed analysis of engineering specifications and industrial conditions
2. Computer aided design and engineering
3. Application of Fluxtrol or Ferrotron magnetic flux controllers
4. Advanced manufacturing techniques

The end result of Power Inductor Technology is the Power Inductor. Power Inductors are more efficient, reliable, and technologically advanced than traditional inductors designed by "Rules of Thumb". Power Inductor Technology is described in the articles "Advanced Design of Induction Heat Treating Coils: Part I & II" [1, 2]. This presentation continues the comparison of Power Inductors to bare coils with special emphasis placed in power control and energy savings.

## Magnetic Flux Control in Induction Coils

The application of magnetic flux controllers is one of the most effective methods for induction coil improvement. In many cases, the coils can not work effectively without flux controllers. In different applications, they play different roles and have different names: - concentrators, controllers, diverters, cores, impeders, shunts, shields. Magnetic flux controllers can provide:

- improvement of the coil electrical efficiency;
- heat pattern improvement due to the possibility to control the distribution of heat sources in the part;
- better utilization of the power transferred into the workpiece;
- protection of the workpiece or induction machine components against unintended heating (shielding);
- improvement of the coil power factor;
- improvement in the coil matching to power source and in efficiency of the supplying circuitry due to lower current demand;
- elimination of the external magnetic fields in close proximity to the coil.

Several of these benefits usually occur when a magnetic flux controller is properly applied. The technical and economical significance of each effect depends on specific conditions of a particular induction heating application. A detailed study on the influence of magnetic flux controllers in induction heating applications has been conducted at the Centre for Induction Technology and Fluxtrol Mfg. using computer simulation and full scale experiments [1,2,3,4]. The results show that the proper application of controllers is always beneficial in an induction heating technique. The specific benefits of a controller depend strongly upon the application type, coil design and magnetic flux controller material.

Besides the traditional materials for magnetic flux control in electromagnetic systems, laminations and ferrites, there is a new type of material on the market called magnetodielectric materials (MDM's). These materials are represented mainly by Fluxtrol and Ferrotron products. The specific features of the different materials for magnetic flux control in induction systems will be discussed at the end of the paper.

The study showed that when applied to I.D. coils, hairpin, pancake, tunnel, split-and-return and single shot induction coils, magnetic flux controllers result in an immediate increase of the coil efficiency and energy (power) savings or a decrease in cycle time [1,2].

Computer simulation study shows that for O.D. coils, the most widely used type in industry, the traditionally defined electrical efficiency of the coil does not change much when a magnetic flux controller is applied. However experiments and industrial practice show that in many cases a tremendous improvement in coil performance takes place, including significant energy savings. Additional study allowed us to solve this puzzle and describe properly the mechanism of energy savings in these types of systems.

Presented below is a profound computer simulation study of local induction heating of a steel block in an oval induction coil (Figure 1). Figure 2 shows two separate cross sections of half of the active area of the system that are used for computer simulation. The top geometry is a Power Inductor and the bottom is a bare inductor. The geometry is exactly the same for both cases with the exception of the flux concentrator. Simulation has been done using a 2-D coupled electromagnetic plus thermal program, Flux 2D [5].

The first study is a comparison of the process parameters when heating with a concentrator and without a concentrator under the condition of equal coil current. This case corresponds not only to energy savings, but even more importantly to the power distribution and resulting temperature control in the length of the coil (local heat control).

The second part of the study corresponds to the condition of equal heating time and maximum part temperature under the coil face. These conditions can be used for a direct comparison of the energy savings from a concentrator in this type of application.

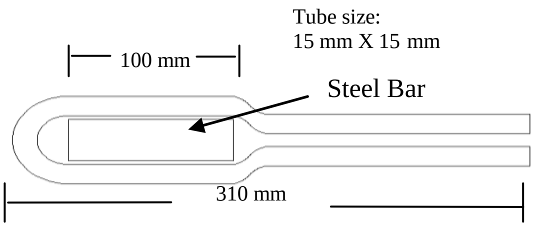

**Figure 1** Cross section of a static heating system

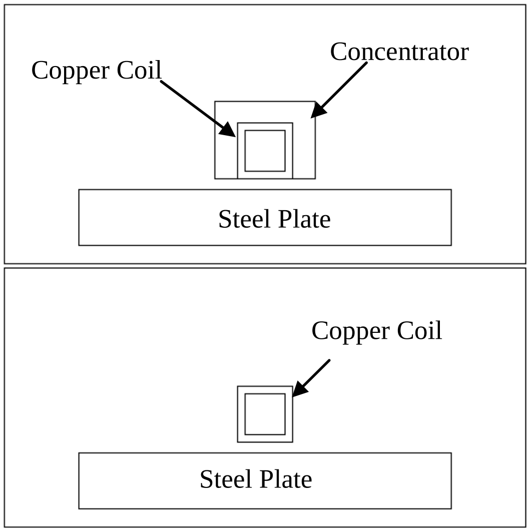

**Figure 2** Half of the geometry used for simulation of static induction heating a steel block
Top: Power Inductor Bottom: Bare Inductor

**Local Heating Control** In a local heating application, the goal is to heat certain areas under the face of the coil. To do this we can apply concentrator to the areas we wish to heat. Because the coil parts with and without concentrator are connected in series, the current for both cases must be the same. The simulation uses a constant current of 4,000 A through both parts of the coil (with and without concentrator). The frequency used for simulation is 3 kHz.

The material used for simulation is 0.4% carbon steel. The minimum austenitizing temperature is 800 C. The maximum allowable temperature is 1000 C. The heating time is 6 seconds.

The magnetic field lines at the end of the heating cycle are shown in Figure 3. There are more field lines around the section with concentrator and the density of the lines is higher. This leads to greater, more concentrated heating in the coil part with concentrator than in the bare area of the inductor. The power induced by the coil part with concentrator is over 4.5 times the power generated by the bare section of the coil.

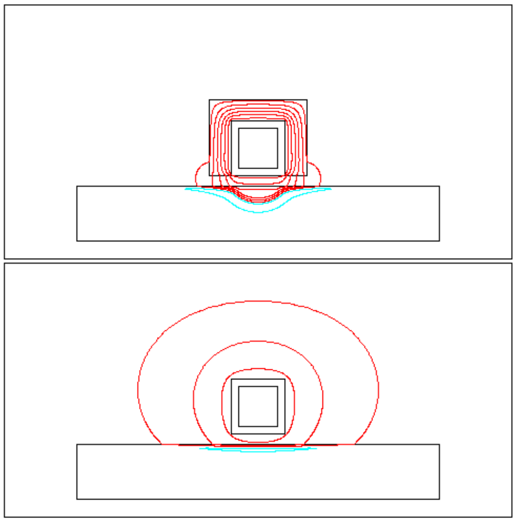

**Figure 3** Magnetic Field lines at the end of heating

Figure 4 shows the temperature distribution in the two sections of the steel block. The maximum temperature steel heated by the bare section of the coil is only 250 C, while the area of the block under the coil part with concentrator heated to 935 C. This produces a tight hardness pattern (Figure 5) under the concentrator, while the areas heated by the bare coil are not hardened at all.

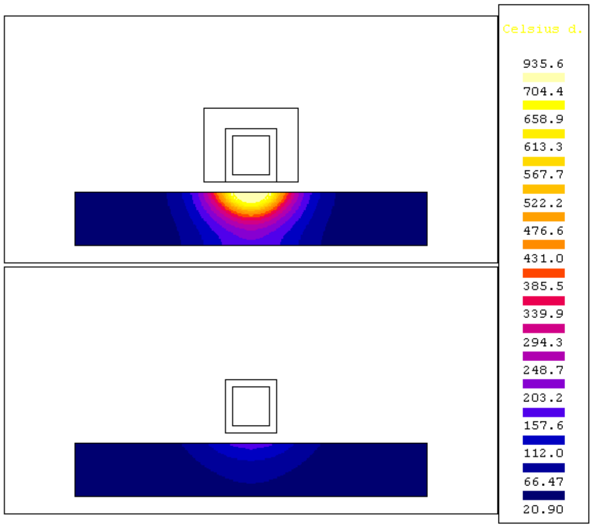

**Figure 4** Temperature distribution in the workpieces with the same current in the coils

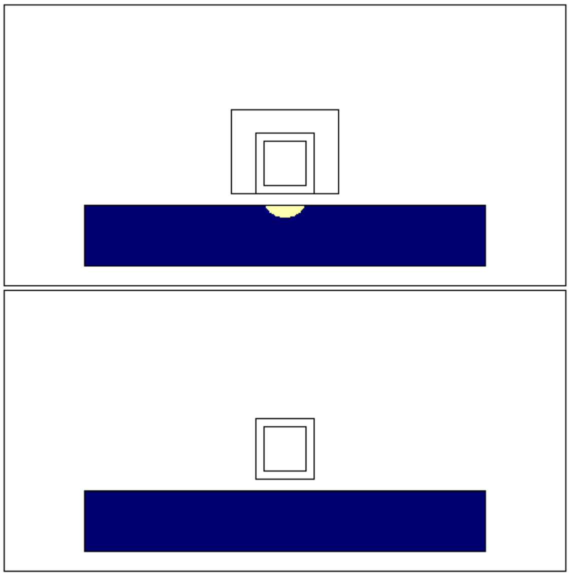

**Figure 5** Austenitized zone in the workpieces with the same current in the coils

The above simulations are done with the same current in the Power Inductor and bare inductor sections. The electrical efficiencies of the two setups are relatively close (89 % for the section with concentrator to 84% for the bare coil), but the temperature distribution and power are drastically different. It means that the use of magnetic flux concentrators allows us to provide distinct power and heating control in the length of the coil. Smooth temperature control may be achieved by using different MDMs along the length of the coil.

**Energy Savings** An argument can be made that by increasing the current in the bare coil, we can successfully heat the block in the same time. This is true, but the question is in what will be the difference in required power or energy between the Power Inductor and the bare inductor. For this study, we heat up the steel to the same maximum temperature in the same time with the Power Inductor and the bare inductor. We can then compare the resulting temperature distributions and energy requirements.

For this case, we applied a different voltage to the two coils for the same amount of time. The voltage was selected for each coil such that the maximum temperature after 6 seconds was the same for both pieces of steel.

Figure 6 shows the final distribution of temperature in the two workpieces. The maximum temperature is 970 C in both pieces of steel. The Power Inductor produces a significantly tighter heat pattern than the bare inductor. Also, the depth of heating is slightly greater for the Power Inductor and the austenitized zones are comparable for both (Figure 7).

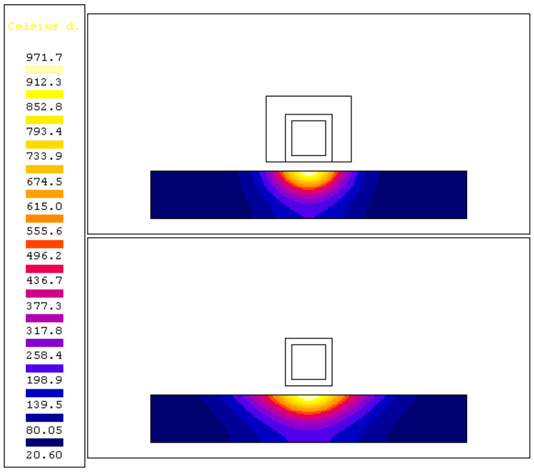

**Figure 6** Temperature distribution in the workpieces with the same maximum temperature

If we look only at the active area of the coil (coil head), the electrical efficiencies of the two coils are close to one another. However, the input power required for the bare coil is 1.5 times greater than for the Power Inductor. In addition, there are 2.5 times more kVA's required for the bare inductor due to the greater current demand (10,100 Amps for bare coil to 4,100 Amps for Power Inductor).

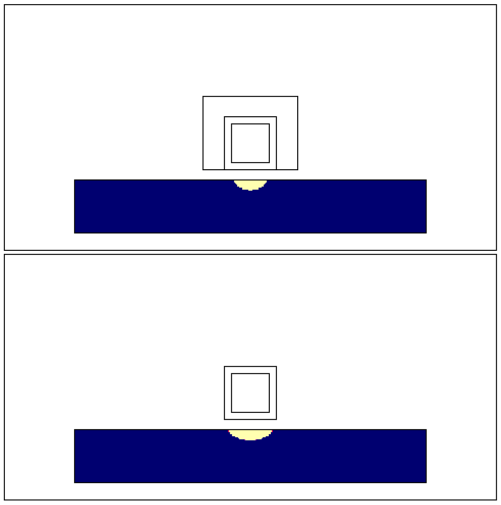

**Figure 7** Austenitized zones in the workpieces with the same maximum temperature

To do a true analysis of the energy savings, we must also take into account the buswork, the transformer and the inverter. The losses in the buswork are proportional to the current in the inductor squared. Therefore, the losses for the bare inductor (18 kW) are 6 times greater than the losses in the Power Inductor (3 kW). The losses in the transformer are approximately proportional to the current squared (winding loss). The total losses in required 500 kVA transformer will be 19 kW for the bare inductor and 3 kW for the Power Inductor. For a modern power supply, the efficiency of the inverter for this frequency can be assumed to be about 94%. This makes the inverter losses for the bare inductor 8 kW and the inverter losses for the Power Inductor are 4 kW (Table 1).

The total power requirement for the bare inductor from the mains is 130 kW. This is almost 2 times the requirement for the Power Inductor (67 kW). To harden the bar with the bare inductor, we would need a 200 kW power supply, because power typically run at 65 to 75% of rated power. For the Power Inductor, we would only need a 100 kW power supply. This would lead to a significant savings on capital investment for the process.

The above analysis shows that even though there is only a small difference in the electrical efficiency of the two coils, the Power Inductor requires much less power due to better utilization of the power inside the workpiece and reduced losses in the buswork, matching transformer and power supply [3].

It means that for correct comparison of coil perfomance, we must consider not only the electrical efficiency, but also the equivalent efficiency of the installation. The equivalent efficiency is the ratio of the minimum power induced in the piece to heat it (power of the steel heated by the Power Inductor) divided by the total power required from the mains. The equivalent efficiency of the bare coil is only 38%. The equivalent efficiency of the Power Inductor is 75%, two times that of the bare coil! A possible reduction in capital equipment costs is another advantage of the use of a Power Inductor in this application.

| | **Bare Coil** | | | | |
|---|---|---|---|---|---|
| | Coil Head | Bus Work | Transformer | Inverter | Overall |
| Coil Current | 10100 | 10100 | 10100 | | 10100 |
| Coil Voltage | 25.4 | 16.5 | | | 42 |
| Coil Power | 13.7 | 18 | 19 | | 51 |
| Steel Power | 71.1 | | | | 71 |
| **Total Power** | **84.8** | **18** | **19** | **8** | **130** |
| El. Efficiency | 83.8 | | | | 55 |
| kVA's | 257 | 167 | 0 | | 423 |
| | **Power Coil** | | | | |
| | Coil Head | Bus Work | Transformer | Inverter | Overall |
| Coil Current | 4100 | 4100 | 4100 | | 4100 |
| Coil Voltage | 26.6 | 6.6 | | | 33 |
| Coil Power | 7 | 3 | 3 | | 13 |
| Steel Power | 49.6 | | | | 50 |
| **Total Power** | **56.6** | **3** | **3** | **4** | **67** |
| El. Efficiency | 87.7 | | | | 75 |
| kVA's | 109 | 27 | | | 136 |

**Table 1** Electromagnetic parameters for the static induction heating system

### Materials For Magnetic Flux Controllers

Requirements for magnetic flux controller materials in induction heating applications can be very severe in many cases [2,4]. They must work in a very wide range of frequencies, possess high permeabilities and saturation flux densities, have stable mechanical properties and good chemical and thermal resistance. In heat treating and brazing applications, the material must withstand an attack of hot water, quenchants or active technological fluxes. Machinability is also a very important property for successful application of flux controllers because it allows you to obtain exact controller shape sometimes rather complicated, necessary to assure consistent results. Three groups of magnetic material may be used for magnetic flux concentration and / or control: laminations, ferrites and magnetodielectric materials (MDM).

Laminations manufactured from silicon steel are a traditional material for low and medium frequency coils and components of electrical equipment. The main frequency range of their application is below 10 kHz though at times they are used at frequencies up to 50 kHz with reduced flux density and intensive cooling. Laminations have high permeability and saturation flux density. Frequency limits, high losses at high frequencies, laborious manufacturing of complex shaped controllers and poor performance in 3D fields are the main drawbacks of laminations.

Ferrites have high permeability in weak fields only, low losses and can work in a wide range of frequencies when properly selected and applied. Some drawbacks restrict their application as a material for flux controllers. They have relatively low saturation flux density and Curie points, are sensitive to thermal and mechanical shocks and may not be machined except by grinding and cutting with diamond tools.

Magnetodielectric materials (MDM) are made from soft magnetic particles and dielectric material which serves as a binder and electric insulator of the particles (1,3,6). Four grades of Fluxtrol™ and two grades of Ferrotron™ magnetodielectric materials now cover almost all the world's induction heating market demands in MDM. They are produced by pressing of different magnetic powders and binders with subsequent thermal treatment according to special technology. "Low" frequency grade (Fluxtrol A) is developed for frequencies up to 30 kHz. Its initial permeability is 65; maximum permeability 120, saturation flux density Bs = 1.6 T. Fluxtrol B has initial permeability 25 and Bs = 1.4 T. It is designed for main frequency range 30 - 200 kHz though it may be used effectively in much wider range of 10 - 450 kHz. High frequency material Ferrotron 559 (permeability 15, Bs = 1.2 T) is formulated for frequencies up to 1.5 MHz. Ferrotron 119 can work at any frequency of induction applications. Its permeability is 9 and its saturates at 1.0 T. All these materials have excellent machinability, can operate continuously at temperatures up to 300 C, and are inert to most quenchants and technological fluxes. Machined pieces of concentrator may be soft soldered to copper (Fluxtrol A), mechanically attached or glued to the coil. Thermally conductive adhesives provide good heat removal from the controller.

## Conclusions

The use of magnetic flux controllers is one of the most effective methods for the improvement of an induction heat treating system. Recent advances in induction heating technology have led to the creation of Power Inductors. Power Inductors are the state-of-the-art inductors with Fluxtrol and Ferrotron magnetic flux controllers. The benefits of Power Coils have been proved by computer simulation, full scale laboratory experiments, and in industry. Previous studies showed significant benefits for magnetic flux concentrators in I.D., split and return, hairpin and many other inductors. A new profound computer simulation study shows that a bare inductor can take twice as much power as a Power Inductor to do an equivalent job in an oval coil installation. This can lead to significant energy and capital equipment savings in these types of processes.

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