

Influence of Magnetic Flux Controllers on Induction Heating Systems, Computer Simulation and Practice

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Abstract

Magnetic flux controllers are used in a wide variety of induction heating processes. However, very few people clearly understand what happens to an induction heating coil when a magnetic flux controller(s) is applied. In addition, formulas for calculating the system performance variation due to the use of magnetic flux controllers are only available for a selective few cases. The magnetic flux controller often has multiple positive effects on an induction heating system such as coil parameter improvement, power distribution control and stray flux elimination. It is difficult to isolate and identify separately these phenomena through empirical methods.

With the emergence of new computer simulation programs, it is now possible to accurately predict the role a magnetic flux controller will have on an induction heating system. It is also possible to optimize the system and take full advantage of the benefits of magnetic flux controllers using computer simulation. Improved induction heating coils and systems are seen in practice due to the application of magnetic flux controllers.

Introduction

Induction heating is more sensitive to the process parameters than other methods of heating. It requires individual process development for each particular part [1, 2]. Induction coils and in some cases other components of the heating installation (matching transformer or even power supply) must be changed when you change the part. Every part

must be handled separately and accurately positioned inside the induction coil. A skilled designer is necessary for the successful design of an effective induction coil. Designer must consider several factors when designing an induction heating coil and process including:

- correct choice of the coil style
- geometry and cross-section of coil tubing
- dimensions and material(s) of the magnetic flux controller(s).
- frequency, power and time
- surrounding induction process environment

The application of magnetic flux controllers is one of the most effective methods for coils improvement. In some cases, the coils can not work properly without flux controllers. In different applications, they play different roles and have different names: concentrators, diverters, cores, impeters, shunts, shields.

While the use of magnetic flux controllers is well known in the induction heating industry, exactly how they work was not well known. In recent years, certain rules of thumb have evolved that for certain types of induction heating coils (i.e. I.D., hairpin, single-shot, vertical loop, split-n-return) a magnetic flux controller should be used. Some other rules have evolved for material selection and magnetic flux controller dimensions. In most cases, these rules will provide significant induction system performance improvement. However, often times these systems are still far from optimized.

In some other applications, a magnetic flux controller may fail. The typical response is to blame the failure on the magnetic flux controller. Most induction heating coil designers do not

have the proper tools or approach necessary to solve this problem and it is much easier to blame the magnetic flux controller than the improper induction coil design. The test and trial method may work in some applications, but a better method is required for others.

Computer simulation is the only way to fully analyze and isolate the particular benefits of a magnetic flux controller and to optimize the induction coil and process parameters. It is also the best way to identify problematic areas in the induction coil design and to reduce the risk of coil failure or improve induction coil lifetime.

The following study is based upon computer simulation of a robotic induction scanning application demonstrated at Fluxtrol Manufacturing, Inc.'s (Fluxtrol) booth at the ASM '99 exhibition. This process was designed to show both the potential for mobile induction heating due to modern high frequency power supplies with flexible cables and portable transformers and to demonstrate the magnitude of the influence of a magnetic flux controller and the ability of computer simulation to predict it.

Robot Guided Induction Scanning

Induction scanning processes have been around for a long time. In a traditional induction scanning application, the part is indexed through a stationary induction heating coil. Stationary induction heating coils are typically used and they are usually connected to the heat station by solid copper busswork. In most cases it is much easier to move the workpiece than the heat station, which for heat treating traditionally are tens of cubic feet and hundreds of pounds.

With a stationary induction heating coil though, you are limited to treating workpieces with certain types of shapes. For instance, a flat plate could be heated with an induction scanning process, but it would be very difficult to scan it if the surface had any undulations or steps.

In the late 1990's, high frequency flexible cables and small, handheld transformers for induction heat treating applications became available. At the same time, small, universal, relatively inexpensive industrial robots were beginning to become available. These advancements combined to open up new possibilities for induction scanning applications

where the coil would move in conjunction with or instead of the workpiece.

To demonstrate the new possibilities for induction scanning, Fluxtrol, Centre for Induction Technology, Inc. (CIT), ABB, EFD Induction and Dry Coolers companies partnered to create a robot guided induction heating demonstration at ASM '99. Dry Coolers provided the closed looped cooling system. EFD contributed an induction heating power supply with flexible cable and handheld transformer. ABB supplied a universal robot, protective cage and platform for the system. CIT developed the demonstration concept and designed the induction heating process and coil through the use of computer simulation. Finally, Fluxtrol provided the inspiration for the demonstration, manufactured the induction heating coil and workpiece, provided the show floor space and coordinated the operation.

CIT had several considerations regarding the demonstration concept. First, the demonstration had to show a process that would have been very difficult without moving the induction coil. Second, the process had to visibly show the advantage of using a magnetic flux controller. Third, the process had to fit to the MINAC 30 power supply EFD was providing. Fourth, there was not a good opportunity to change parts, so the same workpiece had to be able to be treated several times. Finally, the process was going to be run on ASM exhibition show floor.

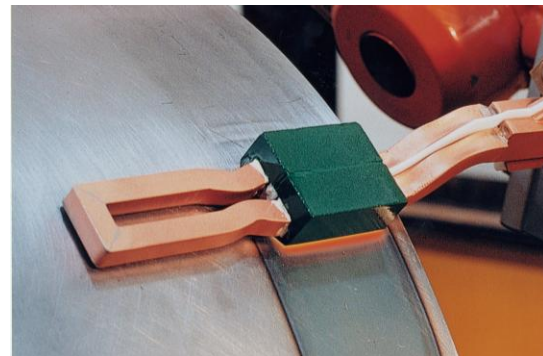


Figure 1. Robotic induction scanning process

The final consideration set the most constraints on the installation design. Because it was on the show floor, the use of quenchant for cooling was not practical. Yet the process had to be performed over and over on the same workpiece and show the effect of the magnetic

flux controller (temperature above 600 C must be at the coil output for visual effect).

CIT decided to use an undulating steel plate that was water cooled from the backside by a continuous water flow. A hairpin style induction coil with Fluxtrol A magnetic flux controller applied to half of the inductor was selected.

Figure 1 shows the robot guided induction scanning process. To optimize this induction coil and process using a 2-D coupled electromagnetic plus thermal program with linear motion would take a great deal of time. The geometry of this hairpin style induction coil is inherently 2-D, but it can be modelled accurately with the 1-D coupled program ELTA. We can consider the system as two separate turns over a flat plate.

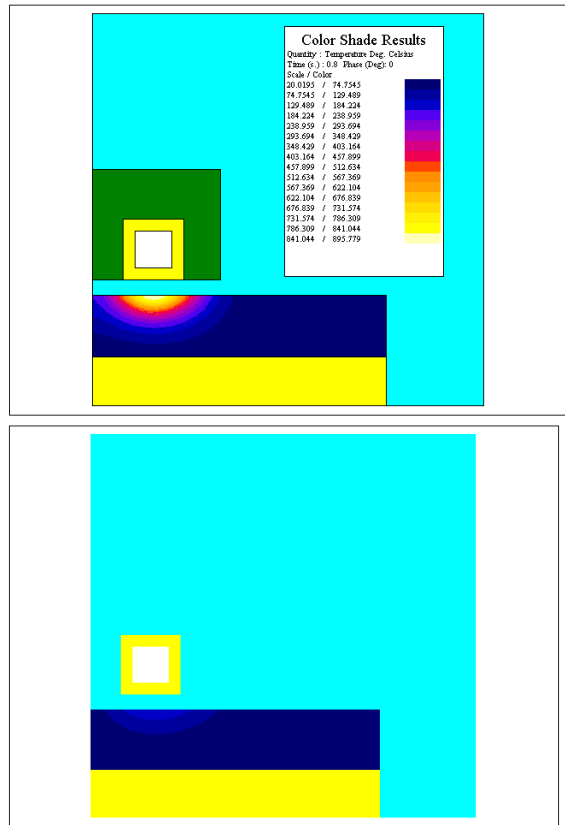


Figure 2. Final temperature distribution with and without concentrator for static heating

Using ELTA, we were able to determine the induction coil dimensions, scanning speed and plate thickness such that the temperature under the heating face would not exceed 950 C and

would remain above 600 C for more than 1 second after it left the induction heating coil.

To determine the difference in heating between the area with Fluxtrol A and without it, both ELTA and Flux 2D coupled simulation were used. Figure 2 shows the resulting temperatures for static 2-D simulation. If static heating were used, the area with concentrator would be heated to more than 900 C, while the area without would be heated to less than 200 C!

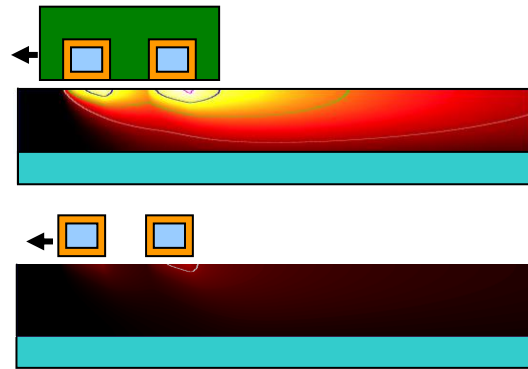


Figure 3. Computer simulation of robotic induction scanning process using ELTA

Using ELTA for scanning simulation, we found that the 1-D approach provided very good results when Fluxtrol A was applied (Figure 3). For the area without concentrator, ELTA provided an overestimate of temperature (350 C compared to 200 C). It is natural that a 1-D program would overevaluate the coil heating efficiency. It did not account for the demagnetizing influence of the adjacent coil conductor, which is much higher without Fluxtrol A.

The installation was constructed based upon the results of computer simulation. When the process was run, the actual performance was almost identical to that predicted by simulation. The power level to produce the maximum temperature and the time of visibility were within 5-10% of predicted values. In addition, the difference between the area with Fluxtrol A and without was very accurately predicted with the Flux 2D. The area without Fluxtrol did not leave any oxides at all on the steel plate, indicating that the temperature was below 250 C, while the area under the concentrator produced the desired 900 C temperature!

Magnetic Flux Controller Application

In some applications, a magnetic flux controller may fail. One of the most common causes of magnetic flux controller failures is improper application technique, especially for Magnetodielectric Materials (MDMs). For induction heating applications, MDMs are the most versatile materials for magnetic flux control and are represented mainly by the Fluxtrol® and Ferrotron® family of materials. Most people don't pay a great deal of attention to the application technique of the material, but in some cases it can increase the induction coil lifetime more than ten times!

In the case of single turn coil, net-shape or machined MDM pieces may be applied to the water cooled coil tubing directly. Soft soldering of MDM to the coil copper provides the best heat transfer. This method is possible only for some types of MDM such as Fluxtrol A. A thin layer of thermally conductive epoxy with alumina, silica or metal powder filling properly applied to the copper provides excellent bonding and superior heat removal.

In multi-turn coils the MDM pieces must often be insulated from the coil copper in order to avoid electric shorts through the material and subsequent thermal breakdown. Low frequency MDMs materials have electric resistivity sufficient to prevent origin of induced eddy currents in the concentrator body but not enough to withstand high external electric voltages. One or two millimeters of silica filled epoxy or silicon glue are usually sufficient for attaching the concentrator to multi-turn coils for heat treatment.

For high voltage coils [>500 V], better electrical insulation must be provided and a separate means of MDM cooling may be required. Properly applied MDMs have been working on some induction heating coils for many years without degradation or notable changes of physical and magnetic properties [3].

MDM Materials and Properties

MDM materials are made from soft magnetic powders and dielectric materials which serve as a binder and electric insulator of the particles [4]. The magnetic properties of these composites depend on the properties of their constituents and the technology of

manufacturing. MDMs have a valuable combination of electromagnetic, thermal and mechanical properties adjustable in a wide range, to match particular process requirements. Modern materials and technologies permit us to provide a complex of magnetic, mechanical, thermal and chemical properties for effective use of MDMs in the induction heating systems.

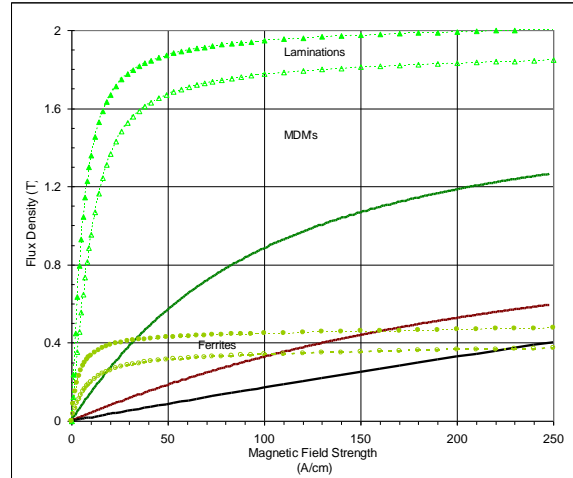


Figure 7. Magnetization curves for laminations, ferrites and magnetodielectrics

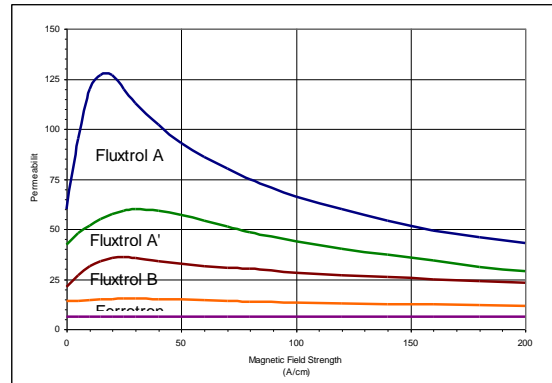


Figure 8. Permeabilities of magnetodielectric materials: Fluxtrol A` - Fluxtrol A in a direction of pressing

MDMs are widely used in power electronics, communications and radio electronics due to their thermal stability and linearity of properties. However, the components for these industries usually have simple shapes and have very large production volumes. These MDM's are usually not machinable, and don't fit well to induction heating requirements. Machinable MDMs now cover almost all the world's induction heating

market demands. They are produced by pressing magnetic powder mixed with a binder, which then undergoes a thermal treatment according to special technology.

“Low frequency” (below 30 kHz) solid materials for induction applications are typically made from atomized or electrolytic iron powder and high temperature organic binder. Permeability and saturation induction rise quickly when the percentage of the binder is reduced. Some kinds of low frequency MDM have maximum permeabilities of up to 500 for application in motors or electromechanical devices. This permeability is achieved with a subsequent decline in electric resistivity and machinability. A reasonable compromise must be reached in material development for a particular field of application. High frequency materials usually have a higher percentage of binder and different magnetic components. Carbonyl iron, iron based alloys or ferrite powder may be used as the magnetic component for frequencies higher than 30 kHz in order to reduce eddy current and hysteresis losses. High frequency materials have lower permeabilities and saturation flux densities.

Fluxtrol and Ferrotron properties.

Solid MDMs have varying degrees of anisotropy. Permeability and saturation flux density are minimal in the direction of pressing and maximum in perpendicular directions. The degree of anisotropy depends on material composition and technology of manufacturing. Anisotropy is significant in low frequency materials (figure 8, curves A and A') and is less significant or negligible in high frequency materials. A coil designer must take into consideration the anisotropy to achieve the optimum results in MDM application.

The Fluxtrol and Ferrotron materials have been designed specifically for use in the induction heating industry. These materials all have excellent machinability, chemical stability, temperature resistance and good magnetic properties. Each grade is designed for a given range of application.

The main material for low and middle frequency (50 Hz – 50 kHz) applications is Fluxtrol A. It has an initial permeability of 60 - 65 and maximum permeability of 120 - 130. The

density of Fluxtrol A is 6.5-6.7 g/cm³. The saturation flux density is 1.6 T.

The middle and high frequency material (10 kHz—500 kHz) for induction heating application is Fluxtrol B. It has an initial permeability of 26 and maximum permeability of around 40. The density is 5.5-5.7 g/cm³. The saturation flux density of Fluxtrol B is 1.4 T.

A new material for the middle and high frequency range (10 kHz to 500 kHz) applications is now available. It has higher permeability, saturation flux density and better thermal properties than Fluxtrol B. This material is presently called “Fluxtrol Bnew”. It has an initial permeability of 35-38 and maximum permeability between 55 and 60. The density of Fluxtrol Bnew is 6.0-6.1 g/cm³. The saturation flux density is 1.4 T.

The high frequency material (10 kHz – 1000 kHz) is Ferrotron 559. Its initial and maximum permeabilities are very close and range from 18-20. The density of Ferrotron 559 is 5.8 – 6.0 g/cm³. The saturation flux density is 1.2 T.

For very high frequency applications (50 kHz - 1000 kHz), Ferrotron 119 is available. Ferrotron 119 has been used at frequencies up to several MHz. Its permeability is almost constant at 8-9 for all field intensities. The density is 5.2 – 5.4 g/cm³. The saturation flux density is 0.8 T.

The Fluxtrol A and B have short term temperature resistances in excess of 250 C and long term temperature resistance in air of about 200 C. The Ferrotron materials (559 and 119) have short term temperature resistances of about 300 C and long term temperature resistance of 250 C in air. In inert atmospheres, both Fluxtrol and Ferrotron materials can operate closer to their short term limits for long periods of time provided there isn't significant mechanical strain on the concentrator.

Conclusions

Magnetic flux controllers play an important role in the induction technique. The environmental conditions for magnetic flux controllers can often be quite severe. There are three main families of materials for magnetic flux controllers: laminations, ferrites and MagnetoDielectric Materials (MDMs). Of these three types of materials, MDMs are the most versatile. MDMs for induction heating

applications are mainly represented by the Fluxtrol and Ferrotron family of materials. Fluxtrol NewB is a new type of MDM for medium to high frequency applications. A robotic induction scanning application was shown to demonstrate new possibilities for the induction technique, the power of magnetic flux controllers and the ability of computer simulation to predict their performance.

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