by Valery I. Rudnev • Inductoheat Group

Electromagnetic forces in induction heating

Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Valery Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director – science and technology. In the past, he was an associate professor at several universities, where he taught graduate and postgraduate courses.
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Electromagnetic (EM) forces play the major part in many modern technologies.[1] Motors, magnetohydrodynamic (MHD) seals, electromagnetic pumps, levitators, electrical bearings, and springs are some of the modern technologies in which EM forces play a leading role. In some applications, EM forces can reach tremendous values. For example, thanks to a capability to develop incredibly large electromagnetic forces, electric guns or launchers can fire materials to higher velocities than are achievable by rockets or chemical / powder guns.[2]

In the majority of induction heating applications, coil current also can reach appreciable values. For example, currents of 10 kA and higher are not unusual for many induction heat treating applications, including shaft hardening and gear hardening. High currents produce significant forces that have a pronounced effect on coil life. Without proper consideration, those forces can physically move the heated workpiece or flux concentrator, and even bend the induction coil or fixture, which may negatively affect overall system reliability and repeatability, as well as dramatically reduce coil life.

Unfortunately, electromagnetic forces are rarely discussed in induction heating publications. Each of the seemingly endless variety of heat treated parts requires a specific coil geometry (Fig. 1), which makes it difficult to study EM forces. This column is intended to at least partially remedy this by providing an introduction to the topic.

How EM Forces Form

A current-carrying conductor placed in a magnetic field experiences a force that is proportional to current and magnetic flux density.[1] Thanks to a study by Ampere and Biot-Savart, this force can be quantified. If current-

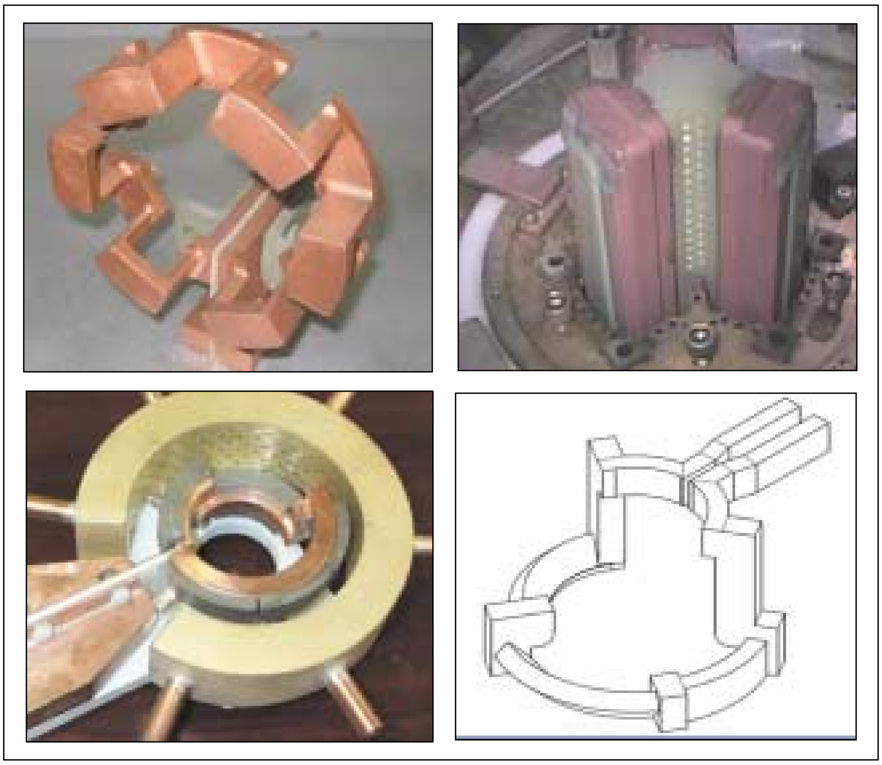

Fig. 1 — Inductors for hardening complex-shaped parts. Photo courtesy Inductoheat Inc.

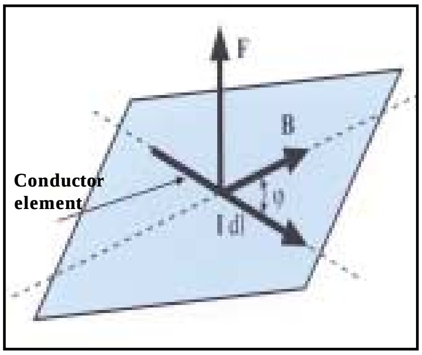

Fig. 2 — Left hand rule (FBL rule) of magnetic force. F = *electromagnetic force.* B = *magnetic flux density.* I = *current.* dl = *element of current-carrying conductor. (Ref. 1)*

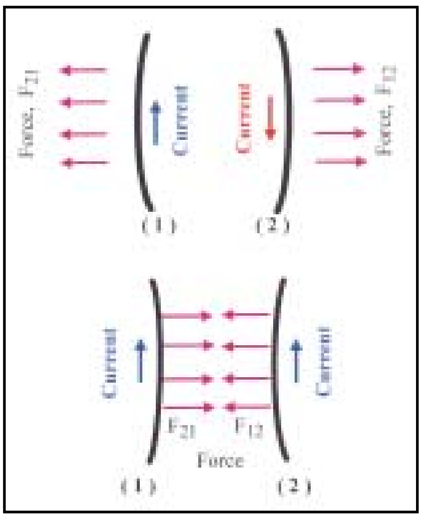

Fig. 3 — Magnetic forces in current-carrying conductors (labeled 1 and 2). When currents flow in opposite directions, top, the electromagnetic forces attempt to push the conductors apart. When currents flow in the same direction, bottom, the EM forces try to squeeze them together. (Ref. 1)

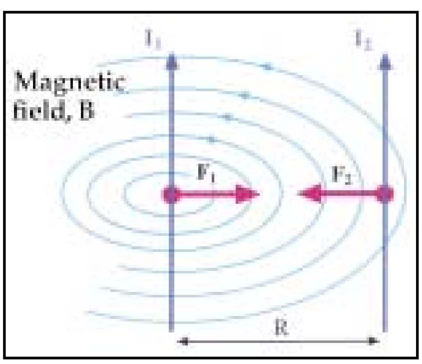

Fig. 4 — The magnetic interaction between two thin current-carrying wires. The currents (I) *are flowing in the same direction.* F *is the EM force.* R *is the distance between the wires.*

carrying element *dl*, carrying a current *I*, is placed in an external magnetic field *B*, it will experience a force *dF* according to:

$$dF = I \times Bdl = IBdl\sin\phi \qquad \text{Eq. 1}$$

F, *I*, and *B* are vectors and ϕ is the angle between the direction of the current *I* and magnetic flux density *B*.

In SI units, the force is measured in newtons (1 N = 0.102 kgf = 0.225 lbf). Figure 2 shows that the direction of the force experienced by the element *dl* of the current-carrying conductor placed in an external magnetic field *B* can be determined based on the left hand rule (*FBL* rule). According to the rule, if the middle finger of the left hand follows the direction of current flow and the pointer finger follows the direction of the magnetic flux of the external field (magnetic field lines head into the palm), then the thumb will show the direction of the force.

It is important to remember from Eq. 1 that, if the angle ϕ between the direction of the current *I* and magnetic field *B* is equal to zero, then $\sin\phi = 0$ and, therefore, *no force* will be experienced by the current-carrying conductor. In other words, if the current-carrying conductor is parallel to an external magnetic field, then it will not experience any force from that field. The lesson here is that magnetic force depends upon orientation of the current-carrying conductors, among other factors.

How Heat Treating Is Affected

But what does EM force mean to induction heat treaters? Consider these common cases of magnetic forces in induction heating applications.[1]

Push apart: If two current-carrying conductors (such as bus bars or cables) having currents flowing in opposite directions are located near each other, then each conductor will experience forces oriented in the opposite direction (Fig. 3, top), which are attempting to separate the conductors, $F_{12} = -F_{21}$.

Squeeze together: In contrast, if two conductors are carrying currents oriented in the same direction (Fig. 3, bottom), the resultant forces will try to bring the conductors together. They will experience an attractive force, $F_{12} = F_{21}$. In some cases, the forces are so large that they can deform bus bars.

What follows are simplified calculations of attractive magnetic forces occurring between two thin wires, each carrying a current of 200 A and separated by a distance of 20 mm (0.8 in.). According to basic electromagnetics, each of the parallel current-carrying wires produces a magnetic field according to the equation:[3]

$$B = \mu_0 I / 2\pi R \qquad \text{Eq. 2}$$

R is the radial distance between the wires (Fig. 4). Therefore, the magnetic force experienced by the second wire, according to Eq. 1, will be:

$F = I_2(\mu_0 I_1 / 2\pi R)l$, and the force per unit length will be $F / l = I_2 (\mu_0 I_1 / 2\pi R)$

In this case, the force per unit length will be:

$$F/l = [4\pi \times 10^{-7}\ \text{Wb} / (\text{A} \times \text{m})(200\ \text{A})^2] / 2\pi(0.02\ \text{m}) = 0.4\ \text{N} / \text{m}$$

Multiturn coils: These phenomena can also be applied to a multiturn solenoid inductor (Fig. 5). Alternating voltage applied to a multiturn solenoid results in a current flow within it, producing electromagnetic forces. Since the currents flowing in each turn of the multiturn solenoid are oriented in the same direction, the turns will experience longitudinal compressive stresses. Assuming an infinitely long solenoid and a homogeneous magnetic field, it can be shown that the longitudinal magnetic pressure (density of the magnetic force in N / m²) f_l inside the long and homogeneous solenoid can be expressed as:

$$f_l = F_l / Area = \mu_0 H_t^2 / 2 = B_t^2 / (2\mu_0) \qquad \text{Eq. 3}$$

In the case of the infinitely long multiturn solenoid, H_t is the root mean square (rms) tangential component of vector *H* (magnetic field intensity).

$$H_t = NI/l \qquad \text{Eq. 4}$$

N is the number of turns in the long solenoid of length *l*, and *I* is the coil current.

At the same time, the turns of the solenoid experience tensile forces in the radial direction, because the current flowing on the opposite side of each turn is oriented in the opposite direction. The radial tensile magnetic pressure f_R can be described as:

$$f_R = \mu_0 H_t^2 / 2 = B_t^2 / (2\mu_0) \qquad \text{Eq. 5}$$

Another assumption used when deriving Equations 3 and 5 is that the solenoid is empty or consists of an infinitely long nonmagnetic load with a constant electrical resistivity. It must be emphasized, that since eddy currents induced by the induction coil within the heated workpiece are oriented in a direction opposite to that of the coil current, the coil turns experience tensile magnetic pressure, whereas the workpiece is under compressive pressure. In order to provide a rigid and reliable coil design, this magnetic pressure should be taken into consideration, particularly for inductors that primarily rely upon proximity heating (pancake, split-return, and butterfly coils, for example) and when using relatively low frequencies to heat metals having low electrical resistivities.

Theory Applied to Real World

The discussion so far has considered only an infinitely long solenoid. However, when the induction coil and workpiece are of finite length (which is the realistic case), the electromagnetic end and edge effects have a pronounced effect on the orientation, value, and distribution of the magnetic forces. Electromagnetic end and edge effects are discussed in detail in Ref. 1. Two typical examples are shown in Fig. 6.

If a nonmagnetic bar is partially placed inside a multiturn inductor to provide, for example, bar-end heating, the magnetic force will try to eject the bar from the coil (Fig. 6, top). Stronger forces result when heating bars of low-electrical-resistivity metals.

However, the situation is quite different when a magnetic bar (carbon steel or cast iron, for instance) is partially placed inside a multiturn inductor (Fig. 6, bottom). The resulting

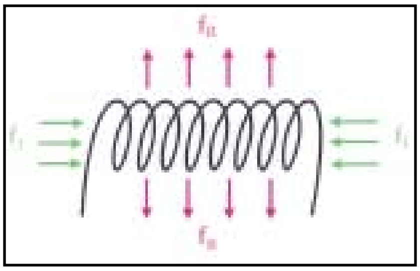

Fig. 5 — Magnetic forces in a multiturn solenoid coil. Since the currents flowing in each turn of the coil are oriented in the same direction, the turns will experience longitudinal compressive stresses. Note: f_l is the longitudinal magnetic pressure, while f_R is the radial tensile magnetic pressure. (Ref. 1)

force is a combination of two forces: one resulting from the demagnetization effect, which attempts to remove the bar from the inductor, and the other resulting from the magnetization effect, which attempts to pull the bar toward the center of the coil. The force due to magnetization is typically the stronger of the two.

Complex forces: In most induction hardening applications, the electromagnetic force has a complex three-dimensional distribution. Depending upon coil design and application, one of three force components — longitudinal, radial, or hoop — may be significantly greater than the others. It is important to remember that the orientation and three-dimensional distribution of forces during the heating cycle is not a function of only the geometry of the system, and is not constant. During the induction heating process, the force distribution also depends on frequency, power density, temperature / material properties, heating mode (constant power, current, voltage), and other parameters.

Bear in mind that the formulas given here can be applied only in some specific / simplified cases. For the majority of induction heating applications having complex-shaped parts and coils (see Fig. 1), a computer modeling study is required to help the designer accurately evaluate the EM forces that will be experienced by the inductor and to determine which actions should be taken to develop robust and reliable coil designs.

A steel shaft example: Proper coil / fixture design should take this

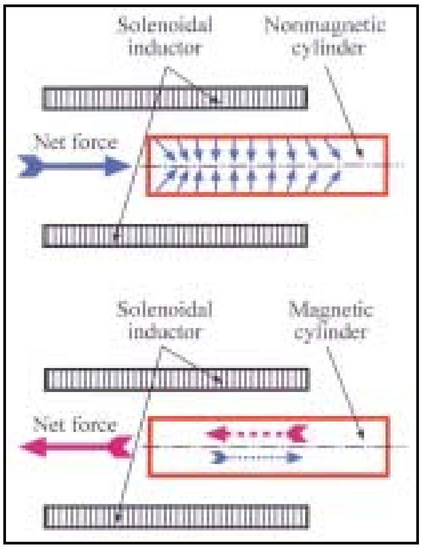

Fig. 6 — Magnetic forces in bar-end heating of nonmagnetic, top, and magnetic, bottom, bars. The force will try to eject a nonmagnetic bar from the coil. Two forces act on a magnetic bar: one attempts to remove it from the inductor, while the other (typically the stronger of the two) tries to pull it toward the center of the coil. (Ref. 1)

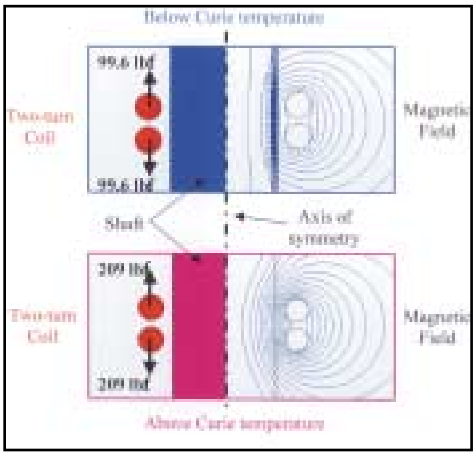

Fig. 7 — Computer modeling plots of the magnetic field distribution and major forces experienced by a two-turn induction coil when heating a steel shaft. Top: shaft temperature below the Curie temperature. Bottom: shaft temperature above the Curie temperature. Coil power and applied frequency were 180 kW and 1 kHz, respectively. Additional information is given in the table. Courtesy Inductoheat Inc.

*Forces produced when induction heating a 50 mm (2 in.) OD steel shaft, N (lbf)**

Force component	Temperature below Curie point	Temperature above Curie point
F_{hoop}	81 (18.2)	298 (67)
$F_{longitudinal}$	443 (99.6)	928 (209)
F_{radial}	1.4 (0.3)	5.2 (1.2)

** Two-turn induction coil, 189 kW power, 1 kHz.*

unequal distribution of electromagnetic forces into account. Numerical computer modeling can provide appreciable help when evaluating them. An example, given in Fig. 7, shows the magnetic field distribution around a two-turn induction coil for hardening a 2 in. (50 mm) OD shaft using a power / frequency combination of 180 kW / 1 kHz.

The table lists the magnetic forces produced when this carbon steel shaft is heated to temperatures below and above the Curie temperature.

When heating above the Curie temperature, each turn of the two-turn coil will experience the maximum longitudinal force of 928 N (209 lbf). Imagine a situation where two adult men, each weighing 95 kg (209 lb), are hanging on each turn of the two-turn coil trying to pull it apart. Obviously, such intensive force cannot be neglected since it dramatically affects coil life, and should be properly taken into consideration when designing induction heating systems. Thus, a special effort should be made to improve coil design, which will help reduce electromagnetic forces and make the overall system more robust.

Conclusion: Depending upon the application, magnetic forces can adversely affect the rigidity and repeatability of an induction heating system, causing premature coil failure, excessive vibration, and too much noise. However, in other applications, those forces can be desirable and play an important role in the process; for example, the electromagnetic stirring effect in an induction melting furnace.

References

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