

# PROFESSOR INDUCTION

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Professor Induction welcomes comments, questions, and suggestions for future columns. Since 1993, Dr. Rudnev has been on the staff of Inductoheat Group, where he currently serves as group director — science and technology.



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## Systematic analysis of induction coil failures

### PART 8: 'GAP-BY-GAP' GEAR HARDENING COILS

*This multipart column presents portions of an in-depth analysis of induction coil failures. The study was initiated by Inductoheat's Aftermarket Department and was conducted over a period of several years by the company's R&D staff.*

*The information presented in this series will give readers an understanding of a broad spectrum of interrelated factors and phenomena that can help them identify the potential causes of a particular induction coil failure.*

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**G**ears are induction hardened by either encircling the part with a coil (so-called spin hardening) or, for larger gears, hardening them “tooth-by-tooth” or “gap-by-gap.”<sup>1,2</sup>

Gears hardened by the tooth-by-tooth or gap-by-gap techniques can be fairly large, having outside diameters of 100 in. (2.5 m) or more, and can weigh several tons. The techniques can be applied to both external and internal gears. However, tooth-by-tooth and gap-by-gap techniques are typically not very suitable for small and fine-pitch gears (module < 6).

**'Gap-by-gap' hardening:** The gap-by-gap technique requires the coil to be symmetrically located between two adjacent teeth. An inductor can be designed to heat only the root and/or flank of the tooth, leaving the tip and tooth core soft, tough, and ductile. There are several coil designs that apply these principles. Popular designs are shown in Fig. 1.

The eddy current pattern induced in the gear by a gap-to-gap inductor is a butterfly-shaped loop.<sup>1</sup> The maximum current density is located in the tooth root area (the center or torso of the butterfly). To achieve this effect, the highest coil current density is found in a corresponding part of the inductor.

A magnetic flux concentrator — typically a stack of laminations — is

used to further increase the power density induced in the root. The laminations are oriented across the gap. When a lamination stack is placed around the current-carrying copper, practically all of the current in the coil will be concentrated on the open surface; the concentrator squeezes the current to that surface. This is an electromagnetic “slot” effect.<sup>1</sup> Concentrating the current within the surface of the coil that faces the tooth fillet improves coil-to-gear magnetic coupling, which results in improved coil electrical efficiency.

Applied frequencies are usually in the 1 to 30 kHz range, although frequencies of 70 kHz and higher have been used in some cases. For example, the NATCO-Delapena (National Automatic Tool Co.-Delapena & Son Ltd.) submerged gap-to-gap technique applies a radio frequency of 450 kHz.<sup>3</sup>

Due to small coil-to-gear air gaps (0.5 to 1 mm [0.02 to 0.04 in.]) and harsh working conditions, gap-to-gap coils on average require extensive maintenance and have a relatively short life compared with inductors that encircle the gear.

The most frequently encountered causes of gap-by-gap inductor failures:

- Coil arcing
- Improper handling and coil abuse
- Copper overheating
- Degradation of laminations

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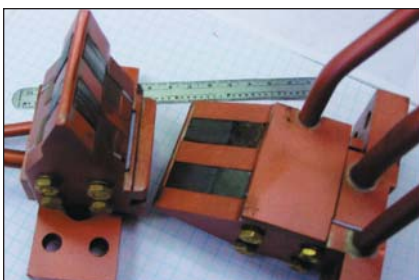


Fig. 1 — Examples of gap-by-gap inductors used for gear hardening.

## Arcing, handling, and coil abuse

Gap-by-gap inductors such as those shown in Fig. 1 are much more sensitive to positioning than are encircling coils. The inductor must be symmetrically located in the gap between two teeth. Nonsymmetrical coil positioning can result in a nonuniform hardness pattern. For example, an increase in the air gap between the coil copper and the fillet surface on one side will result in a reduction of hardness and shallower case depth in that region of the gear. An air gap reduction can cause coil-to-gear arcing, leading to premature coil failure.

**Distortion:** There can be appreciable shape/size distortion when applying gap-by-gap techniques for hardening gears. Shape distortion is particularly noticeable in the last heating position — this last tooth can be pushed out 0.1 to 0.3 mm (0.004 to 0.012 in.).

Shape distortion and metal expansion as well as improper alignment can cause the coil to strike the gear, leading to coil abuse that results in failure. Therefore, metal thermal expansion during heating should be taken into consideration when determining the proper coil-to-gear tooth air gap. Special locators are often used to ensure proper inductor positioning in the tooth space.

In summary, precise coil fabrication techniques, inductor rigidity, and careful inductor alignment are required to avoid premature coil failure.

## Copper overheating

Coil copper overheating is another common cause of coil failure. Relatively small coil-to-gear gaps lead to appreciable thermal radiation from the heated surface. This factor in combination with a very limited space allowed for water cooling of the coil can result in copper overheating, particularly when the scanning mode is used for hardening.

Both tooth-by-tooth and gap-by-gap techniques can be used in submerged hardening, where the gear is submerged in a temperature-controlled tank of quenchant. This was the basis of the original Delapena induction

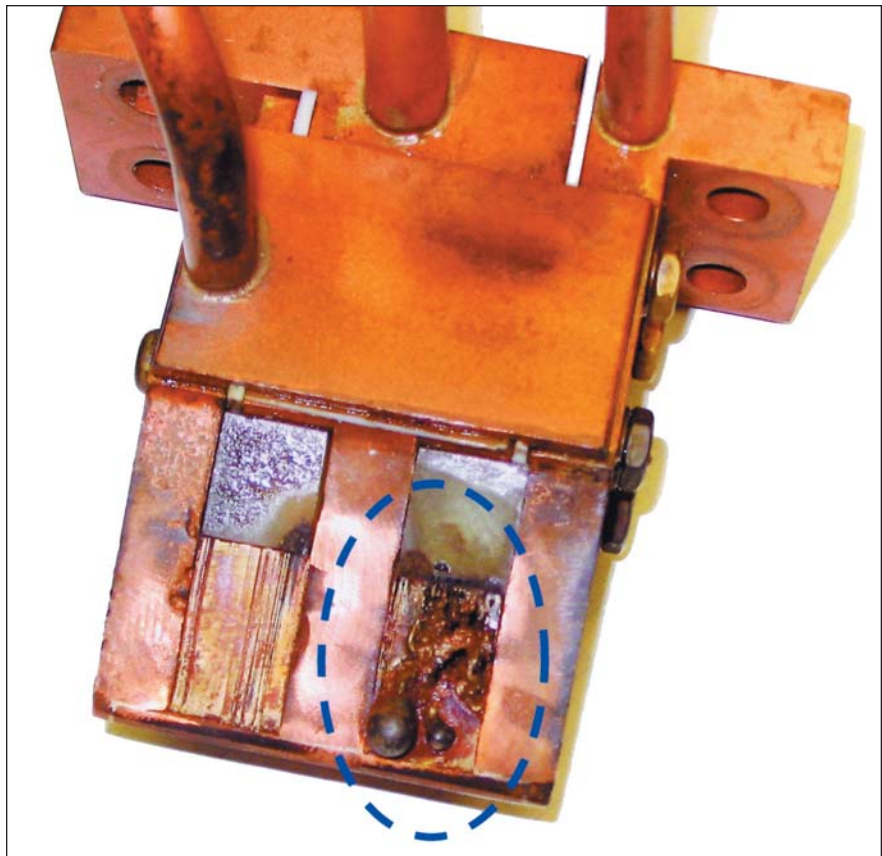


Fig. 2 — This gap-by-gap inductor failed prematurely by overheating of magnetic flux concentrator laminations. Overheated area is circled.

gear hardening process. In this method, quenching is practically instantaneous and both controllability and repeatability of the hardness pattern are improved, although additional power is required. In addition, the quenchant doubles as an inductor coolant. Therefore, a major advantage of submerged hardening is that the induction coil does not have to be water cooled.


## Degradation of laminations

Laminations can be exposed to several harsh working conditions that could lead to their premature failure:<sup>4,5</sup>

- Small space available for concentrators results in a high flux density.
- High coil currents also result in high power densities that could lead to saturation of laminations and their overheating (Fig. 2). The corners and end-faces of laminations tend to overheat due to electromagnetic end and edge effects. Special lamination design features can be incorporated to reduce the risk of overheating.
- Laminations are sensitive to ag-

gressive environments such as quenching solutions.

Rust and degradation can result.

The prediction of coil working conditions through computer modeling is a much better route to perfecting coil design and avoiding premature coil failure than the cut-and-try approach. Proper coil fabrication and maintenance also are important to long inductor life. 

## References

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