by Valery I. Rudnev, FASM, Inductoheat Group

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. In the past, he was an associate professor at several universities. His expertise is in materials science, metallurgy, heat treating, applied electromagnetics, computer modeling, and process development. Dr. Rudnev is a member of the editorial boards of several journals, including *Microstructure and Materials Properties* and *Materials and Product Technology.* He has 28 years of experience in induction heating. Credits include 16 patents and 128 scientific and engineering publications.

Contact Dr. Rudnev at Inductoheat Group
32251 North Avis Drive
Madison Heights, MI 48071
tel: 248/629-5055; fax: 248/589-1062
e-mail: rudnev@inductoheat.com
Web: www.inductoheat.com

Systematic analysis of induction coil failures

PART 9: CLAMSHELL INDUCTORS

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.

Parts 1–8 appeared in the August, September/October, and November/December 2005, and January/February, March/April, May/June, September/October, and November/December 2006 issues.

The main considerations for choosing an inductor style are the shape of the part, the area to be heated or the desired heat treated pattern, and the method of material handling to be used for production. Material handling methods include moving the part into the coil and indexing the coil into the part. Part rotation, if required, and how the part is transferred after it has been heat treated may also be important.[1]

When hardening irregularly shaped components (Fig. 1), adjoining areas may sometimes exclude the possibility of positioning the component inside a cylindrical coil. In other cases, the required "coil-to-part" air gap that would provide enough clearance for loading and unloading the workpiece is so large that it dramatically reduces coil electrical efficiency or may even prevent obtaining required hardened patterns due to an unfavorable combination of coil-end effect and part geometry. An example is the hardening of camshaft lobes that have a sharp "nose" and undersized "base circle" in combination with large bearings or eccentric journals. In cases such as this, split or clamshell inductors (Fig. 2) sometimes provide a solution.

Clamshell coil benefits: Clamshell inductors are so named because they are typically hinged on one side so that the part can be loaded in the correct heating position.

For hardening applications, quenching can be integrated into the coil (Fig. 2) or quench blocks can be placed adjacent to the inductor. Depending upon the application, coil copper can be profiled to replicate the part's shape, which provides a minimum and consistent coil-to-part coupling (air gap). The result: highly efficient heating and a uniform heating profile around the perimeter of an irregularly shaped part.

Locating pins are often required on the inside of the clamshell inductor or on some areas of the part to ensure that the part maintains its position throughout the heating and quenching cycle.[1] The benefits of an even heating pattern on an irregularly

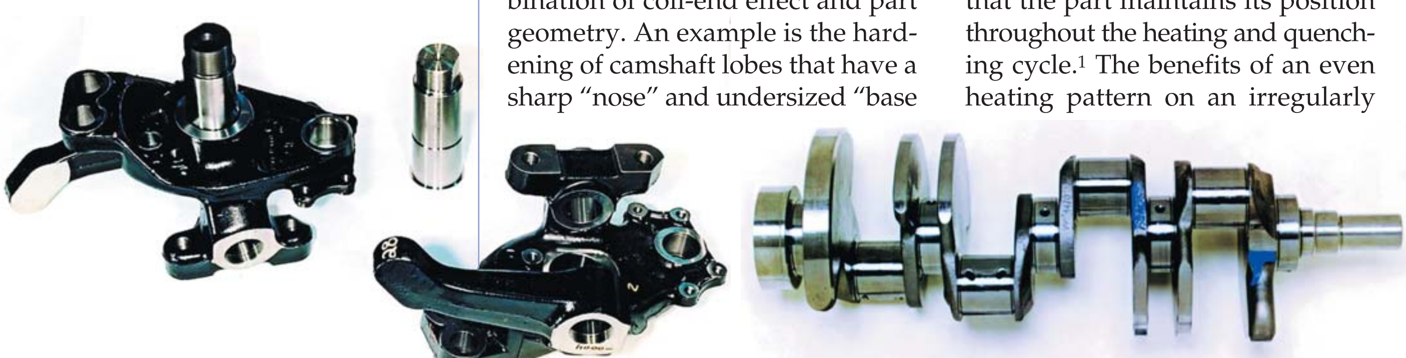

Fig. 1 — Examples of complex-shaped parts that may require use of clamshell inductors.

shaped part obtained by using locating pins are sometimes offset by an adverse effect on production rate.

If locating pins are used inside of medium- or high-frequency coils, then ceramic pins are typically chosen. However, ceramics are brittle and can fail prematurely due to improper part handling, abuse, or thermal shock from heating and quenching.

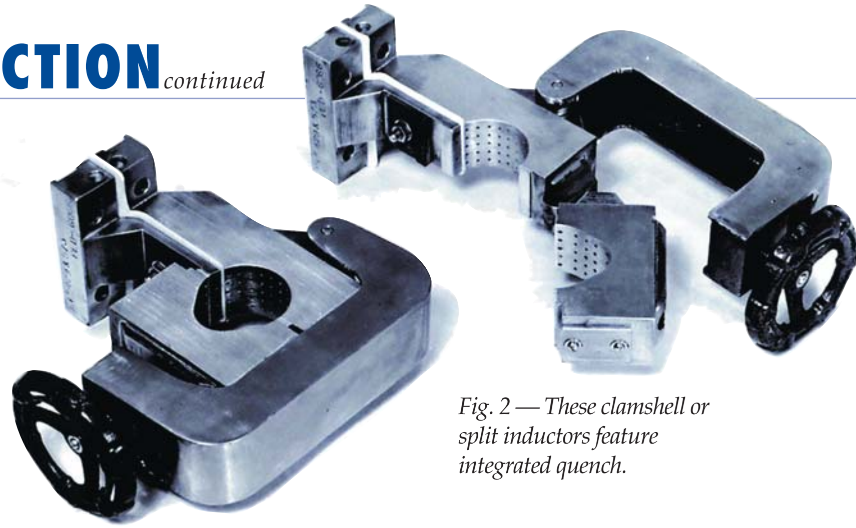

Fig. 2 — These clamshell or split inductors feature integrated quench.

Coil drawbacks: Short coil life, poor reliability, and low production rates are some of the main disadvantages of clamshell inductors. Short coil life results from the inherent need to break the current path by having high-current contacts.

The contact area is the weakest link of these inductors and the main reason for their short coil life. When the inductor is closed, it must be clamped with sufficient pressure to ensure that good electrical contact is made between the movable parts. Realistically, there are no contact surfaces of a coil that are perfectly smooth. Thus, surface roughness has the largest impact on coil electrical current flow through the contact area.

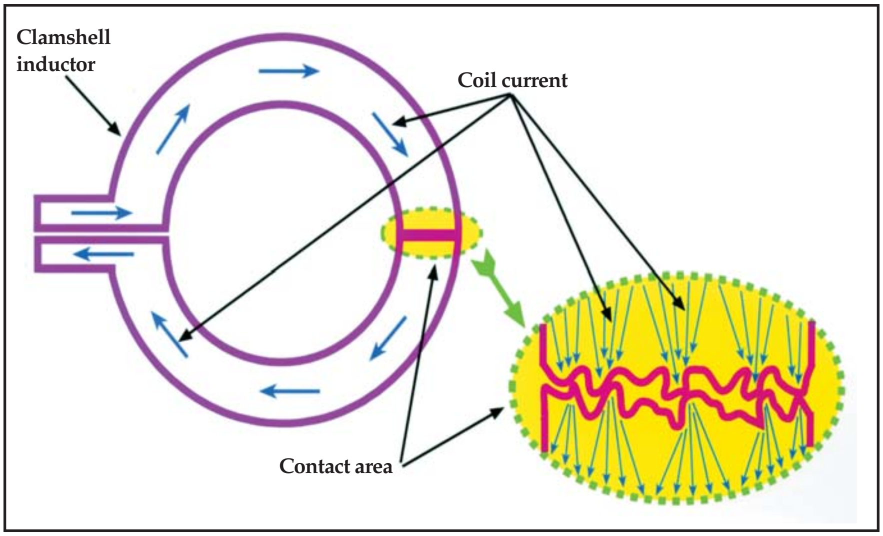

Fig. 3 — Coil current flow in a clamshell inductor.

Regardless of the amount of polishing, air pockets will be present that force the coil current to flow through the solid-to-solid contact points. What results is the appearance of a localized increase of current density and an increase in electrical resistance of the contact area (Fig. 3), compared with solid copper areas of the coil.

Figure 4 shows the equivalent electrical circuit of a clamshell inductor. Since the same current flows through both coil copper and coil contact area, the latter region will experience much greater heat generation due to I^2R Joule losses. Electrical resistance of the contact surfaces is usually more than 10-fold that of solid copper, and heat generation is directly proportional to change in electrical resistance.

The clamping area of the coil also contributes to short inductor life due to wear and contaminants, which can lead to excessive overheating and even arcing, and, ultimately, to premature coil failure. The quality of the electrical contact degrades appreciably after multiple openings and closings of the coil. And contaminants quickly build up on contact surfaces, which also increase electrical resistance of the contact area.

These factors cause the electrical resistance of transitional areas between contact surfaces to continuously change during coil operation, resulting in variation in the power induced within the heated part and, consequently, variation in the heat pattern. Heat treaters often are required to increase the contact pressure to compensate for a clamshell coil's time-dependent power loss. This practice can result in coil copper deformation in clamping areas and coil failure.

Possible remedy? Silver alloy plating is commonly used in an attempt to improve coil life and reduce electrical resistance of coil clamping areas. Unfortunately, it does not appreciably improve coil life. The life of a clamshell inductor usually does not exceed 10,000 heats, and only 3000 or 4000 heats is not uncommon.

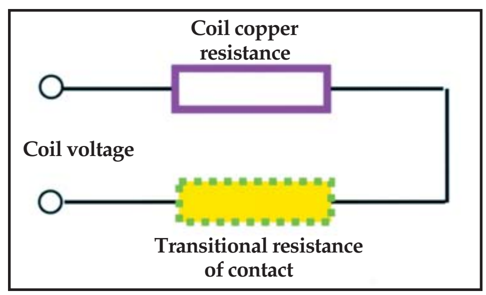

Fig. 4 — Equivalent electrical circuit of a clamshell inductor.

Induction heating equipment manufacturers are continuing their search for ways to extend coil life. The next column in this series will discuss innovative contact-less coil designs that are alternatives to clamshell inductors, and boast substantially longer coil life.

Reference

1. *Handbook of Induction Heating*, by V. Rudnev, D. Loveless, R. Cook, and M. Black: Marcel Dekker Inc., New York, 2003, 800 p.