Computer Modeling Helps Prevent Failures of Heat Treated Components

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Computer modeling can help preclude failure of heat treated parts by taking into consideration the operating requirements of the part and the specific heat treatment.

Consider this scenario. Following the development stage, an induction hardening machine is built, completes a successful run-out, and is shipped to the customer. After a number of successful production runs, parts begin to experience cracking during the hardening operation. A check of induction machine process parameters (power, frequency, quenchant temperature, concentration, pressure and flow, part positioning inside induction coil, etc.) shows everything is in order. The question is why does cracking in parts suddenly occur? Such an occurrence could present a challenge in determining the root cause of cracking and ways to eliminate it. Cracking that occurs during induction hardening often exposes failures that occurred during earlier processing stages, including, but not limited to, the quality of steel, and imperfections in the material caused by casting, rolling, forging, machining, etc.

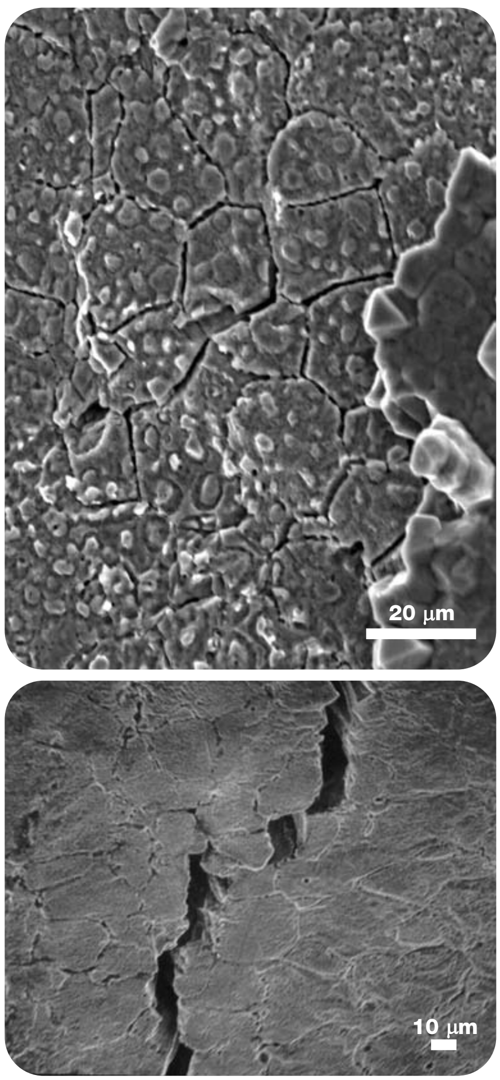

Fig. 1 — *Grain boundary liquation (top) and cracking (bottom).*

While it is important to consider the probability of imperfections created during the processes mentioned above when searching for root cause of cracking during induction hardening, it is also important to consider factors related to a deviation in a part's dimensional tolerances, design features, and process recipes as potential causes of cracking. This article, using two example cases, focuses on design features and process recipes.

Example 1

Overheating is one of the most common causes of cracking. Overheating can lead to unwanted metallurgical microstructures, excessive grain growth, scale formation, and decarburization, as well as grain boundary liquation (incipient melting), which weakens grain structure and substantially increases the steel's brittleness and sensitivity to developing intergranular cracking upon quenching (Fig. 1). Certain design features make a part prone to overheat upon induction heating. Typical examples are parts containing longitudinal and/or transverse holes, keyways, grooves, shoulders, flanges, diameter changes, undercuts, hollow areas, splines, and sharp corners (Fig.2). However, such features are not unique as they are commonly found on many transmission and engine components.

The presence of these features distorts the magnetic field generated by an inductor during scan hardening, which results in two important electromagnetic phenomena: the proximity effect and end effect [1]. Both effects can cause the appearance of hot or cold spots, excessive shape distortion, undesirable microstructures, grain boundary liquation, and cracking. The eddy current flow and temperature fields should be carefully evaluated to determine the appropriate process parameters and coil design to prevent cracking.

In induction hardening of irregular shaped parts, the coil designer has to take into consideration hot spots produced by a power surplus and cold spots caused by insufficient heating during induction hardening. For example, Fig. 3 shows the temperature distribution during

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Fig. 2 — *Representative part having various geometrical discontinuities.*

scan hardening of a hollow shaft obtained by means of finite element analysis (FEA) computer modeling using Inductoheat's proprietary software. During scanning, the magnetic field preferably couples to the shoulder on the shaft generating a power density surplus, which could potentially result in overheating and subsequent cracking. A proximity effect can also manifest itself as a heat source deficit occurring in the undercut region of the shaft and transition area near shaft's smaller diameter, potentially resulting in mixed partially transformed structures upon quenching. The complexity of the electromagnetic field in the area where the diameter changes requires a coil design and appropriate process recipe that address the surplus of induced power in the shoulder of the large diameter and a power deficit in the fillet or undercut of the neighboring smaller diameter area.

The majority of today's commercial software programs are not capable of modeling induction scan hardening. Many of the programs used to model induction heating processes are all-purpose programs originally developed to model processes occurring in electrical machines, motors, antennas, and magnetic recording systems, and were

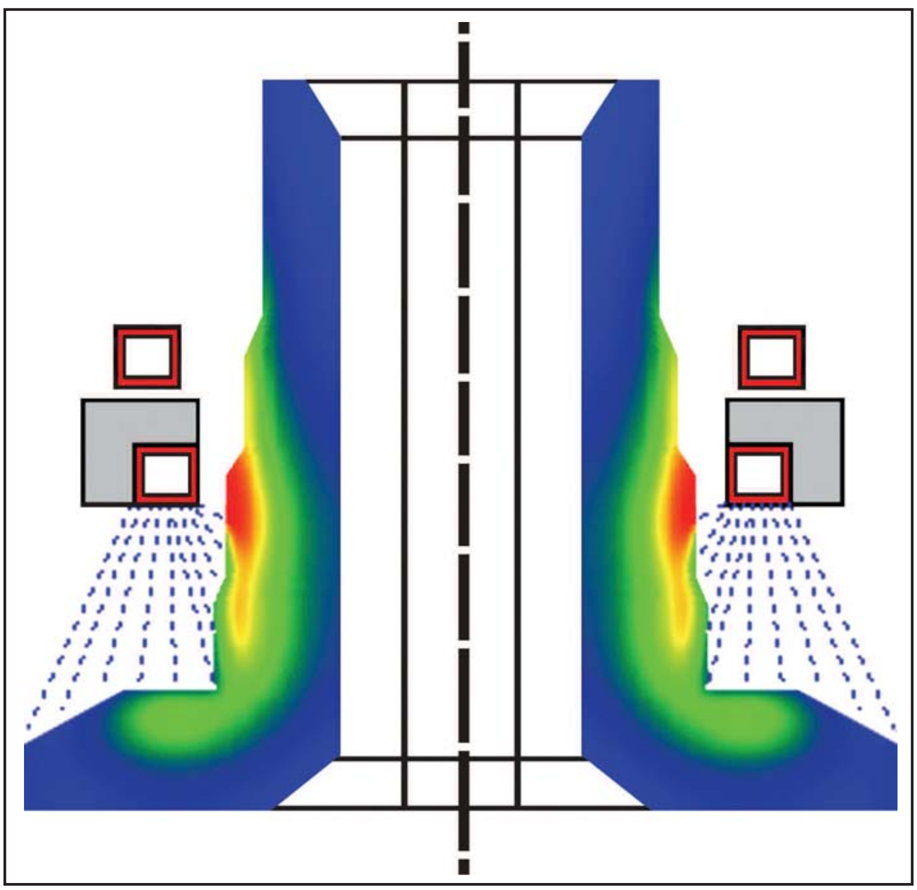

Fig. 3 — *FEA computer modeling of vertical scan hardening of a hollow shaft. Courtesy of Inductoheat Inc.*

later adapted to induction heating. They are limited in their ability to take into consideration certain features of a particular induction heating application including:

- A heated component can simultaneously move, rotate, or oscillate within the induction coil
- Most induction hardening operations combine heating and quenching stages
- Thermal radiation from nearby thermal refractories
- The presence of end plates, guides, fixtures, flux concentrators, etc.

These factors could lead to erroneous modeling results. Inductoheat developed proprietary application-oriented programs that take into consideration process specifics and important subtleties.

To optimize temperature distribution prior to quenching, complex control algorithms are required with varying power and scan rate when the coil approaches variations in part geometry. The need to determine multiparameter control algorithms leads to long development times in the lab using the trial and error method with a number of components being wasted. The learning curve can be considerably shortened and number of parts required for trials can be dramatically reduced thanks to computer modeling.

Mathematical modeling helps determine not only optimal process parameters and inductor design, but also to evaluate the robustness of a particular hardening process by estimating, for example, the impact of real-life process deviations at certain temperatures. This helps reduce the possibility of cracking. Real-life deviations include:

- Dimensional tolerances of the part
- Fixture integrity; i.e., bearing wear, inappropriate gaging, part wobbling, etc.
- Part-to-inductor coupling values (air gaps)
- Tool setup variations; e.g., fabrication accuracy and precision of assembly

Results of computer modeling are helpful not only to preclude premature failure of already designed components, but also to provide important information for component designers by taking into consideration the operating requirements of the part and the specific heat treatment.

Example 2

Computer modeling allows induction heating designers to determine details of a process that could be costly, time consuming, and in some cases difficult or impossible to determine experimentally. To illustrate, Fig. 4 shows the results of computer modeling of the sequential dynamics of induction scan hardening of a hollow shaft that has diameter changes, undercuts, and a groove. Because the shaft is symmetrical, only the top half was mod-

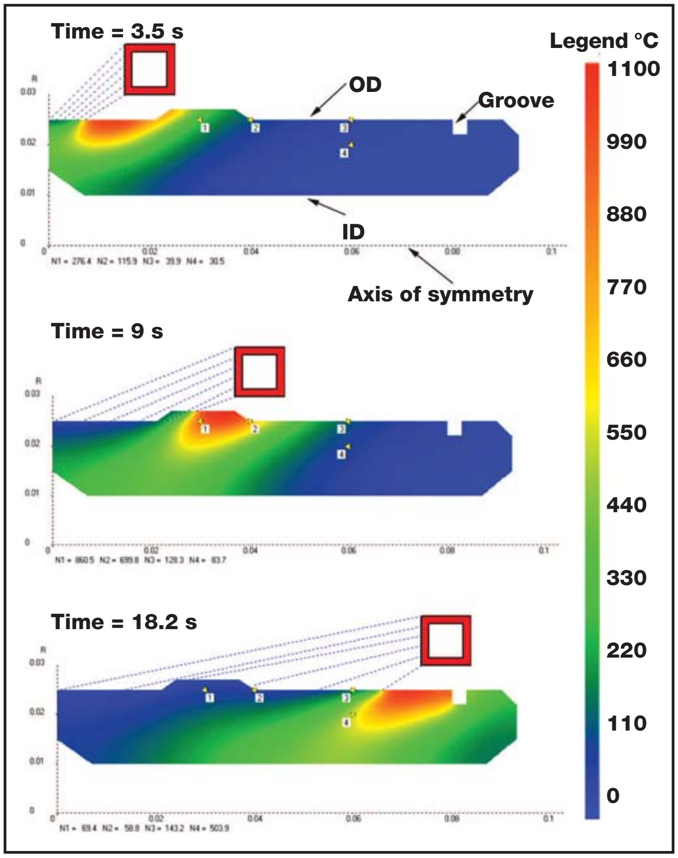

Fig. 4 — *Computer modeling of sequential dynamics of induction scan hardening of hollow shaft with diameter changes, undercut, and groove. Courtesy of Inductoheat Inc.*

eled using FEA analysis. Temperature variations at four selected areas of the shaft are shown, as well at different scan inductor positions. The scan rate and coil power were varied during scanning to accommodate changes in part shape. Computer modeling reveals several important process subtleties.

During scanning, considerable heating of the shaft begins appreciably in front of the copper turn, creating a preheating effect. Axial heat flow due to thermal conduction is one of two factors responsible for preheating. The propagation of the external magnetic field causing generation of heat sources outside the induction coil is another factor. The presence of an external magnetic field outside of the induction coil is also responsible for the post-heating of shaft areas located immediately behind the inductor, and, in some cases, even in regions where the quenchant impinges on the surface of the shaft. This can reduce quenching severity and potentially create conditions for crossing the "nose" of the continuous cooling transformation (CCT) curve resulting in the formation of mixed microstructures with the presence of upper transformation products (for example, bainitic/pearlitic structures or "ghost" networking). Such structures are notorious for causing nonuniform hardening and lower hardness readings, and could potentially lead to a premature failure.

The "comet-tail" effect manifests itself as a heat accumulation in subsurface regions of the shaft behind the scan inductor. It is particularly pronounced in the regions of a diameter change.

Upon quenching, the temperature of shaft surface can be cooled sufficiently below the M_s temperature. At the same time, heat accumulated in the subsurface regions might be sufficient to cause an undesirable tempering back of as-quenched surface regions, leading to soft spots and undesirable shaft properties.

Fig. 5 — *Cracking of the hole located at the change in shaft diameter.*

In some cases, it is required that the hardened case should be prevented at an undercut. In other cases, hardening is required in these areas, such as hardening snap-ring grooves. This requires developing precise control algorithms that provide appropriate coil power variations when needed and terminating power when approaching groove or undercut regions. For example, the bottom scan positioning in Fig.4 shows a process stage when the inductor power is off, but spray-quenching is still applied.

The ability to model a comet-tail effect is limited in many commercial induction heating software programs. Also, some all-purpose programs cannot properly handle pre- and post-heating effects of scan hardening. These restrictions dramatically limit the use of such programs.

Overheating alone might not result in crack development. There are other factors that can add to overheating and increase crack sensitivity. Holes, poor chamfering, and edges are among other geometry-related factors that can increase the tendency for cracking. A fishbone diagram of causes of cracking in induction hardening can be found in Ref. [2].

Size, location, and orientation of a hole can have a marked effect on eddy current flow. The presence of holes can be exacerbated by their location. An undesirable temperature distribution can occur when holes are located at regions of a change in shaft diameter. A combined effect could occur, creating an increased potential for cracking (Fig.5).

Selection of appropriate process parameters often considerably reduces hot spots around the hole and eliminates cracking. Inductor profiling also dramatically reduces hot spots. Computer modeling provides vital assistance in determining optimal inductor profiling.

Prevention of the oil-hole overheating is the first step in elimination of crack development. A second equally important step is avoiding an undesirable distribution and magnitude of transitional and residual stresses. Predicting the formation of stresses during and after induction hardening requires expert modeling and simulation. For example, Fig. 6 shows a computer prediction of austenite transformation around oil hole during quenching. ❍

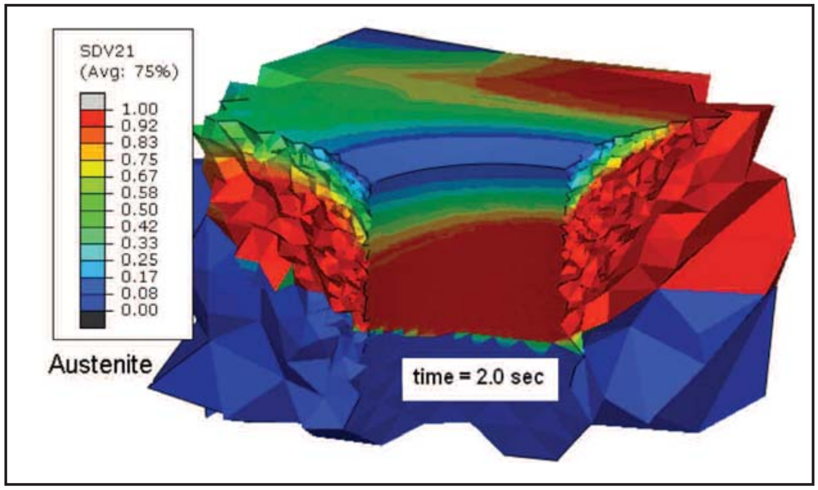

Fig. 6 — *Computer prediction of austenite transformation. Courtesy of Deformation Control Technology Inc.*

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