

by Dr. Valery I. Rudnev, FASM, Inductoheat Group

INDUCTION HEATING

This month's column features the answer to a reader's question about what can be done to eliminate cracking around holes when induction hardening the steel shafts

Q&A

Question: We experience cracking problem around the holes when hardening our steel shafts. What can be done to eliminate it?

Answer: Inappropriate design parameters may result in developing cracks near the holes. As an example, Fig. 1 shows cracks that were initiated around transverse (Fig. 1a) and longitudinal (Fig. 1b) holes. The most frequent cause of cracking is severe overheating. Overheating can lead to unwanted metallurgical microstructures, excessive grain growth, scale, shape distortion, and decarburization, as well as grain boundary liquation, which weakens grain structure and substantially increases brittleness and sensitivity to developing intergranular cracking upon quenching (Fig. 2).

Size, location, and orientation of a hole can have a marked effect on eddy current flow and severity of overheating. It is beneficial to review factors responsible for overheating of the holes while induction hardening shafts^[1,2].

Longitudinal (axial) holes

The presence of longitudinal holes within the part



Fig. 1 — Cracks initiated in proximity to transverse hole (a) and longitudinal hole (b).

can cause a redistribution of eddy current flow, resulting in overheating of certain regions of the shaft. Figure 3 (left) shows a transverse segment of a shaft and the normal current flow within it^[1]. This current distribution is typical if the heated shaft is solid, or if a hole is located significantly below the current penetration depth (δ); therefore, the induced eddy current does not interact with the hole. However, if a longitudinal hole is located within the current penetration depth, it partially blocks the normal eddy current path (Fig. 3, right), squeezes current flow into a channel between the part surface and the hole, and that may lead to a dramatically increased current density and a severe local overheating of hole areas resulting in permanent damage of the steel grain structure.

There are two factors that can cause the overheating:

- An increase of power density (heat source) due to the redistribution of eddy current flow
- The lack of adjacent mass of metal there, meaning that there will be reduced heat transfer from the hot surface of the shaft toward the colder core due to the thermal conductivity (cold sink effect)

Depending on shaft geometry, the impact of both factors may be different. If a longitudinal hole is located within one current penetra-

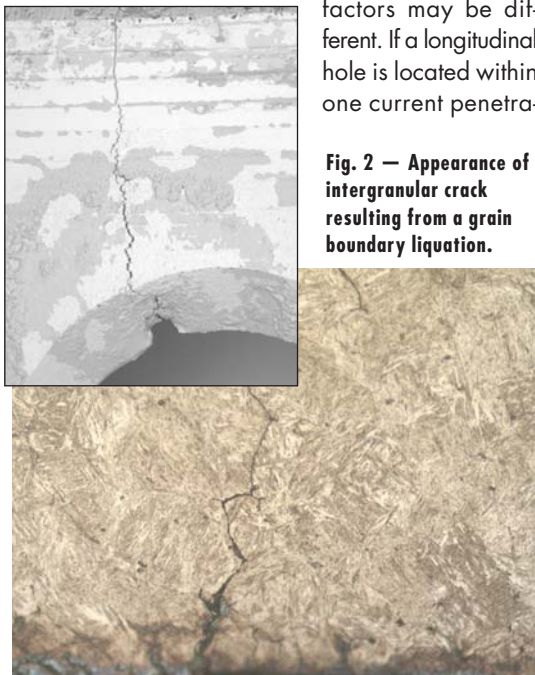


Fig. 2 — Appearance of intergranular crack resulting from a grain boundary liquation.



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. He has 28 years of experience in induction heating. His expertise is in materials science, metallurgy, electromagnetics, heat treating, computer modeling, and process development. Credits include 21 patents and 154 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; www.inductoheat.com.

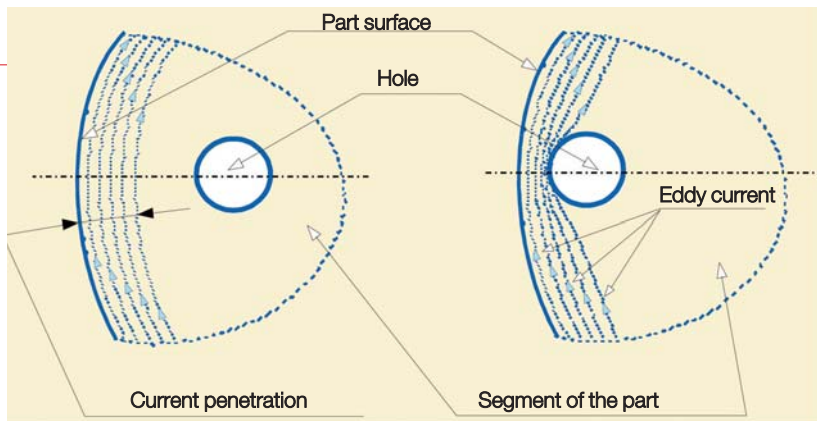


Fig. 3 — Eddy current redistribution as result of the presence of a longitudinal hole^[1].

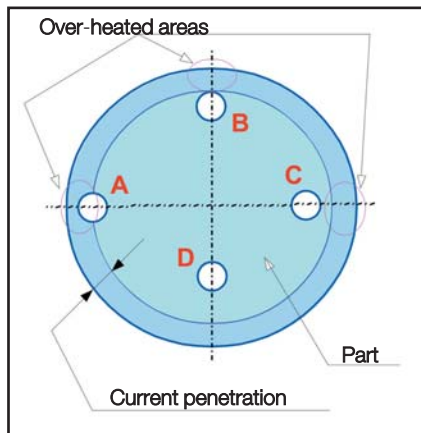


Fig. 4 — Overheated areas due to the presence of longitudinal holes^[1].

tion depth in hot steel (δ) from the shaft surface, then the first factor typically prevails and primarily is responsible for the overheating in that area (Fig. 4, hole A).

When the hole is located within 1 to 2 times the current penetration depth (δ), as with holes B and C in Fig. 4, then both factors have approximately the same impact on the localized heat surplus. If the longitudinal hole is located within 2 to 3 times δ and the heat cycle is relatively long (8-12 s), the second factor typically makes greater contribution to the overheating. When the hole is located sufficiently far away from the shaft surface (Fig.4, hole D), the prob-

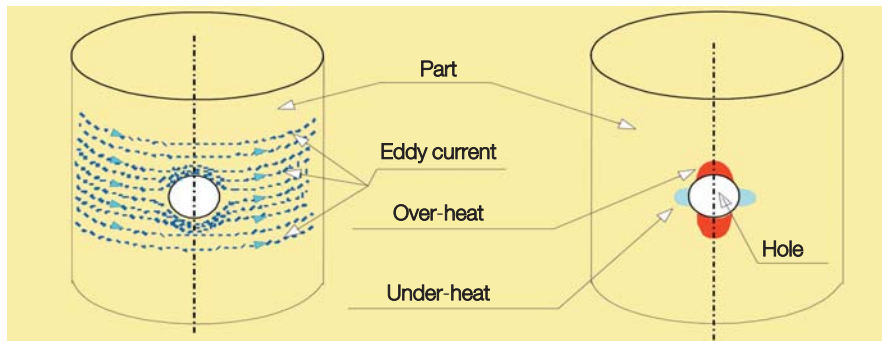


Fig. 5 — Eddy current distribution and heat non-uniformity appearance due to the presence of a transverse hole^[1].

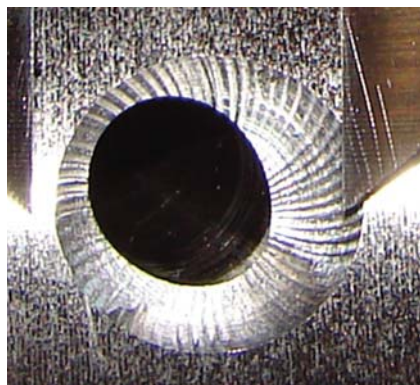


Fig. 6 — Undesirable chamfering having excessive chattering.

ability of overheating is very slim.

Many times, an increase in frequency and/or power density reduction can dramatically reduce an overheating of longitudinal holes eliminating cracking.

Transverse holes

Transverse holes always cause a redistribution of eddy current flow. Unlike the case of longitudinal holes, eddy current redistribution due to transverse holes can result in both under-heating and overheating of the hole edges (Fig.5). Due to the current concentration, overheating can occur at the hole edges parallel to the eddy current flow. At the same time, there will be a certain lack of heat at the hole edges

perpendicular to the eddy current flow. If the hole diameter is less than one half of current penetration depth, that current flow distortion does not typically result in appreciable temperature non-uniformity around the hole. Lower frequencies and power densities typically reduce overheating. An increase in hole diameter makes over-heating more pronounced.

Angled holes

Angled holes located at shaft surface require special attention because the eddy current flow and heat pattern formation combine the features of longitudinal and transverse holes. The sharper the angle of the hole results in a more pronounced overheating and a greater possibility of cracking unless using a profiled inductor design that addresses those features^[1].

Other factors

Overheating alone might not result in crack development. There are other factors that can complement overheating, increasing crack sensitivity. Steel chemical composition is one of those factors. Steels having higher carbon contents are more prone to cracking. Besides carbon content, there also are other chemical elements that affect crack sensitivity; the extent depends on the amount and combination of elements present. Alloying elements are purposely added to provide specific properties such as strength or toughness. Other elements just happen to be in steel in trace amounts or as residual impurities of raw materials. An unfavorable combination of the latter elements could promote a tendency to cracking^[1].

For example, sulfur and phosphorus amounts should be minimized to reduce steel brittleness and crack sensitivity. Sulfur reacts with iron, producing hard, brittle iron sulfides (FeS) that concentrate at grain boundaries. FeS also has a relatively low melting temperature, potentially leading to grain boundary liquation and increased sensitivity to intergranular cracking. FeS in carbon steels is minimized by the addition of manganese to form manganese sulfides (MnS), which are distributed within grains rather than at grain boundaries, creating a less brittle microstructure. A high level of phosphorous also can cause excessive brittleness in both steels and cast irons.

Using lower than optimal quench temperatures, higher than specified quench

flow rates and pressures, and lower quenchant concentrations can initiate hole cracking. These and other quench parameters should be verified if cracking suddenly appears.

Process/inductor design features

As discussed above, selection of appropriate process parameters often allow considerably reducing hot spots around the hole area, eliminating cracking problems. At the same time, there are a number of other helpful practical solutions and know-how available for heat treaters to substantially reduce overheating.

In single-shot induction hardening applications, profiling of inductor copper often allows dramatically reducing or eliminating hot spots in the vicinity of holes. Several patented approaches related to inductor profiling around oil holes were created during the development of the non-rotational crankshaft hardening technology^[3-5]. Those approaches allow selectively controlling heat sources along the oil hole perimeter by providing preferable channels to eddy current flow. It is

also beneficial to orient the part in such a way that coil "fish-tail"^[6] would be positioned near the oil hole, allowing electromagnetic fringing to help reduce the temperature of hot spots.

It is good practice to have holes generously chamfered and free of machine marks, burrs, and chattering. Excessive chattering (Fig.6) and large unfavorably oriented inclusions and strainers might act as stress risers, triggering cracking.

It is possible to obtain a relatively uniform temperature distribution along the perimeter of the hole by putting metallic or nonmetallic plugs into the hole. More information about elimination of hole cracking can be found in Ref.1.

Magnafluxing is an effective nondestructive testing tool that helps to reveal whether surface cracks are present or not. According to this technique, the part is wetted using a solution that contains iron oxide particles and placed in a magnetic field. The magnetized part is inspected using an ultraviolet light. Particles attracted to surface discontinuities (such as cracks) become visible under the light.

Conclusion

Experience shows that in many cases, the proper choice of design parameters (applied frequency, power density, coil profiling, etc.) allows obtaining the required hardened pattern around holes free of cracks, even in those cases that might seem first unsuitable for heat treating by induction^[1]. **HTP**

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