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Metallurgical insights for induction heat treaters

PART 5: SUPER-HARDENING PHENOMENON

Entries in the "Metallurgical insights for induction heat treaters" series alternate with those in the "Systematic analysis of induction coil failures" series.

Hardening of steels represents the most popular application of induction heat treatment. Hardening may be done for the purpose of obtaining certain properties that include, but are not limited to, strength, fatigue, and wear resistance. Different applications and part geometry require certain hardness profiles on the workpiece. Three most common forms of induction hardening are surface hardening (case hardening), through hardening, and selective hardening as shown in Fig. 1[1].

The goal of induction surface hardening is to provide a martensitic layer on surface areas (external and/or internal) of the workpiece that allows improving certain properties of the part without affecting the rest of the part. This is accomplished by raising only the required surface depth of steel above the transformation temperature to a point where it transforms to austenite and is then rapidly cooled. As an example, Fig. 1 (top) shows induction surface hardening of camshaft lobes.

In contrast to surface hardening, the goal of through hardening is to provide a martensitic structure throughout the entire workpiece. For this to occur, the entire cross section is raised above the transformation temperature and then rapidly cooled to produce a consistent martensitic structure through the entire cross section. The ability of the component to be through hardened depends upon the hardenability of the steel, the quenching conditions, grain size, and geometry[1]. Through hardening may be needed for parts requiring high strength, such as snow-plow blades, springs, chain links, truck-bed frames, and certain fasteners. Figure 1 (middle) shows induction through hardening of carbon steel pins.

Both induction through and surface (case) hardening can be localized to selective areas that require selective hardening, a process often referred to as selective hardening. Figure 1 (bottom) shows an example of selective induction hardening of the head of a hammer.

Fig. 1 — Examples of induction hardening; induction surface hardening of camshaft lobes (top), induction through hardening of carbon steel pins (middle), and selective induction hardening of the head of the hammer (bottom).

Super-hardening phenomenon

Hardness distribution along the workpiece radius (in the case of a cylindrical body) or thickness is noticeably different for surface (case) hardening and through hardening. Figure 2 shows a comparison of typical hardness profiles after induction surface hardening and through hardening of a carbon steel cylinder[1]. Figure 2 shows that surface hardness of case hardened parts can be slightly higher compared with surface hardening of identical parts that are through hardened. This phenomenon sometimes is referred to as super-hardening[1-3]. Due to this phenomenon, for given carbon steel, the surface hardness of a part case hardened using induction could be 2-4 HRC higher than normally obtained for a given carbon content for a through-hardened steel.

The super-hardening phenom-

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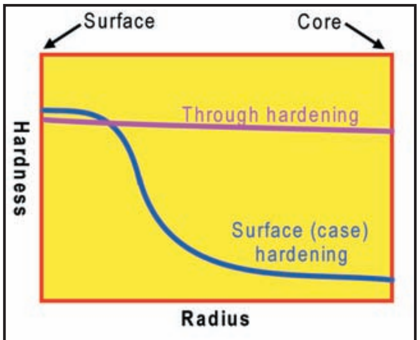

Fig. 2 — Typical hardness profiles after surface hardening and through hardening of a carbon-steel cylinder.

enon is not clearly understood and its origin has not been established, but it can be attributed to several factors including residual stresses and final microstructure (carbide shape and density, retained austenite, dislocation density of the martensitic matrix, grain size, and others). The short heating cycle results in fine austenitic grain sizes that occur because in induction hardening, the steel typically is at the austenitizing temperature for a short time, reducing the possibility of grain growth.

Another factor that might contribute to super-hardening is the higher lattice strain from appreciable residual compressive stresses at the surface of the part when its internal regions, and in particular, the core remain at a lower temperature or at ambient temperature.

In addition, the existence of a cold core that serves as a cold heat sink has a marked effect on the severity of the cooling rate during quenching. In induction surface hardening (case hardening) applications, the core temperature does not rise significantly due primarily to a pronounced concentration of electromagnetic energy within the surface layer (skin effect), high heat intensity, and short heating time. As a result, heat transfer from the surface of the workpiece to its core during the heating stage is not sufficient to significantly raise the core temperature[1]. The total quench severity during the quenching stage of heat treating is a product of the severity of surface cooling by the quenchant and internal cooling due to thermal conduction of heat from the hot surface toward the cold core—the so-called "cold heat sink" phenomenon [4,5]. A cold core complements surface quenching by further increasing the cooling intensity at the surface and subsurface regions of the part. In contrast, hot internal areas of the through-heated parts provide undesirable (in most cases) thermal support to part's surface region that is being quenched by a quenchant by decreasing the total value of quench severity.

Prior microstructure also has a pronounced effect on the appearance of the super-hardening phenomenon. Fine grain homogenous normalized structures, as well as quenched and tempered structures have more of a chance to exhibit super-hardening.

The phenomenon of super-hardening of induction surface (case) hardened parts is particularly noticeable in steels with a carbon content of 0.35 to 0.65%, case depths less than 0.125 in. (3.2

mm) and heat times less than four seconds.

Case study

According to end-quench hardenability test data adapted from *Heat Treating Guide: Practice and Procedures for Irons and Steels*, the maximum hardness range for AISI 1038 steel at a distance of 1mm from quenched surface should not exceed 58 HRC and can be as low as 51 HRC[6]. However, induction surface hardening practice shows that when hardening the pins and main journals of a crankshaft using non-rotational SHarP-C technology (heat time is about 3 s and case depth is approximately 2.3 mm) using a low-concentration polymer quench, hardness readings at 1mm below the part's surface can easily be 60-61 HRC. Even at a distance of about 2 mm below the surface, the hardness remains at the same 60-61HRC level instead of the expected maximum hardness of 55 HRC as predicted by end-quench hardenability test[6]. It was possible to provide a sufficient cooling severity and obtain surface hardness of about 53-56 HRC by just relying exclusively on the cold sink effect (no use of liquid quenchant).

Conclusion

The phenomenon of super-hardening of induction surface (case) hardened parts is particularly noticeable in steels with a carbon content of 0.35 to 0.65%, case depths less than 0.125 in. (3.2 mm), and heat times less than 4 s. Fine-grain homogeneous normalized prior-structures, as well as quenched and tempered structures have more chance to exhibit super-hardening. Annealed and spheroidized prior structures seldom reveal this phenomenon. The super-hardening phenomenon could allow a user to apply a lower steel grade (lower carbon content) without sacrificing the desired surface hardness and hardness profile of the product. **HTP**

References

1. V. Rudnev, D. Loveless, R. Cook, and M. Black, *Handbook of Induction Heating*, Marcel Dekker, New York, 2003.
2. G.F. Golovin and M.M. Zamjatin, *High-Frequency Induction Heat Treating*, St. Petersburg, Russia, 1990.
3. L.C.F.Canale, C.R.Brooks, T.R.Watkins, and V.Rudnev, Effect of prior microstructure on the hardness and residual stress distribution in induction hardened steels, Proc. SAE Intl. Off-Highway Cong., Las Vegas, Nev., March 19-21, 2002.
4. V. Rudnev, Metallurgical insights for induction heat treaters, Part 2: Spray quenching subtleties, *Heat Treating Progress*, ASM Intl., p 19-20, August 2007.
5. V. Rudnev, Metallurgical insights for induction heat treaters, Part 3: Limitations of TTT and CCT Diagrams, *Heat Treating Progress*, p 23–25, Nov./Dec. 2007.
6. *Heat Treating Guide: Practice and Procedures for Irons and Steels*, ASM Intl., Materials Park, Ohio, p 173, 1995.