Dr. **Valery Rudnev,** known as "Professor Induction", discusses in the heat processing different aspects of induction heating, novel theoretical and practical knowledge related to different heat treating technologies accumulated in the North America and around the globe.

Specifics of induction hardening of powder metallurgy (P/M) components

During the last decade, the use of advanced powder metallurgy (P/M) materials in several industries has been expanded at an impressive pace further penetrating markets of demanding applications; however, the biggest market for ferrous P/M components remains to be the transportation industry, particularly the automotive and agricultural sectors. An ability to manufacture net-shape complex geometries offering competitive performance at an economical cost is an attractive feature of P/M parts (e. g. gears, timing sprockets, cams, splined hubs, shafts, shock absorbers etc.) [1]. Density and porosity in the sintered compact are major factors affecting strength and hardenability of ferrous P/M materials; both properties have also been noticeably improved in the last decade. As an example, **Fig. 1** shows a selection of P/M gears and gear-like components that regularly undergo induction surface hardening demonstrating impressive static and dynamic properties that closely approach respected properties fully dense wrought gearing materials.

Similar to steels, alloying helps enhance a desirable combination of strength, load-bearing capacity, ductility, and fracture resistance of P/M materials. Mo, Cu, Ni as well as Cr, Si, P, Mn are some of commonly used alloying elements in ferrous hardenable P/M materials. Some of those elements provide critically beneficial synergistic effects. Carbon content is another major factor that affects achievable hardness and strength. Recently developed lean P/M alloys preserve important performance characteristics of their higher alloyed counterparts and are also noticeably more homogeneous with minimized level of chemical segregation and dusting compared to P/M materials produced even 5–8 years ago.

Induction hardening (IH) of P/M materials has several subtleties compared to wrought steels. These features primarily deal with the marked difference in physical properties noticeably affecting the P/M's response to induction heating and spray quenching.

Challenges associated with differences in thermal properties of P/M materials are common for any type of heat treatment. However, differences in electromagnetic properties are specific for processing those materials applying electromagnetic induction. **Table 1** summarizes the effect of density reduction and porosity increase on IH.

The relative magnetic permeability μ_r of P/M materials is considerably lower than the μ_r of the corresponding wrought steels, while their electrical resistivities ρ are greater to some extent. Both factors lead to noticeably larger current penetration depth (δ) during the heating cycle, affecting not only heat generation and temperature profiles but also the magnitude and distribution of transient and residual stresses as well as coil electrical parameters. These features make hardening protocols for P/M materials appreciably different compared to hardening wrought equivalents.

Lower thermal conductivity of porous P/M parts encourages the development of localized hot spots and excessive thermal gradients and also requires the use of quenchants with intensified cooling rates to obtain the required hardness and case depths, because an increase in pore fraction and a reduction in density negatively affect the hardenability of P/M materials compared to their wrought equivalents.

Water (containing appropriate additives) and aqueous polymer solutions of various concentrations (with 2–10 % being the most typical) with some type of rust inhibitors are often used in surface hardening P/M parts. Rust inhibitors help prevent internal corrosion.

Fig. 1: An array of a variety of P/M gears and gear-like components regularly undergo induction surface hardening [1]

Table 1: How induction hardening of P/M parts is affected by density reduction (porosity increase) compared to their wrought equivalents [1]

Property	Change	Influence on induction process
Thermal conductivity	Decrease	Less soaking action from high-temperature to low-temperature regions. Larger temperature gradients and thermal stresses during heating. Slower cooling of sub-surface regions during quenching
Electrical resistivity	Increase	Larger current penetration depth (δ)
Magnetic permeability	Decrease	Larger δ and lower coil electrical efficiency
Hardenability	Decrease	More severe quench is required to provide the same case depth
Structural homogeneity	Worse	Inconsistency of hardening; variations in surface hardness, case depth, hardness scatter, and residual stress data. Increased tendency for cracking during hardening

Oil quenching is sometimes specified when hardening P/M materials, particularly for those with stringent dimensional stability requirements and those having a pronounced tendency to cracking. Concern about fires and environmental restrictions are obvious drawbacks to using oils and oil-based quenchants. Note that quench oils may require higher temperatures than polymer quenchants. For example, in order to reduce the crack sensitivity of a gear-like component (DIN Sint D11 / ISO P2045) containing holes, it was specified having gentle preheating in the furnace and induction hardening using dunk quench in oil or comparable high concentration polymer quenchant followed by tempering were specified. Besides preheating and in order to avoid delayed brittleness, it was also important to minimize the HAZ as well as peak temperature and to apply the proprietary tempering protocol immediately after quenching.

It is good practice to have a minimum density of at least 7.0 g/cm^3. This helps to improve heat treat consistency. When hardening surfaces that have cuts, shoulders, teeth, holes, splines, slots, sharp edges, and other geometrical discontinuities and stress risers, it is preferable to have a minimum density of 7.2 g/cm^3.

Obviously, density and porosity are not the only factors that affect IH of P/M materials. Other factors include the material composition, homogeneity of the microstructure (the rate of material segregation), surface conditions (including, surface roughness), as well as specifics of prior processing operations such as sintering essentials of the green compact. Double-pressed components and high-temperature sintering improve density, microstructural homogeneity and ensure good diffusion. Under certain conditions, structural heterogeneity may even affect an eddy current flow. Any degree of surface decarburization prior to IH should be avoided.

The alloying method used to produce the powder can also have a marked effect on heat treat results. Among alloying techniques are admixing, diffusion alloying, pre-alloying, hybrid alloying, and the MIM (metal injection molding) method.

Depending on the specific composition, some P/M parts may have a greater tendency to crack. For example, special attention must be paid when developing hardening protocols for copper alloyed P/M materials. Though ferrous P/M materials with a high copper content provide a good blend of mechanical properties at a competitive cost, they are often more prone to cracking. Besides, there is always a legitimate concern in regard to incipient melting when using copper alloyed ferrous P/M utilizing elevated hardening temperatures. This makes it imperative to have sufficiently accurate process control and monitoring.

Case study discussed in [1] reveals that the microstructural heterogeneity in a copper alloyed P/M component may be so severe that, when examined under a microscope, it almost looked like copper had been electroplated on the surface of the part. This was the result of incomplete copper diffusion during alloying and such heterogeneity can easily result in the re-direction of the localized eddy current flow if RF frequencies are applied.

Although it is strongly recommended that P/M induction-hardened parts should preferably have a density of not less than 7.0 g/cm^3, there are a number of successful applications where an O.D. hardening has been done on P/M components with a density as low as 6.8 g/cm^3.

In some cases, it might be considered beneficial if P/M parts have a variable "surface-to-subsurface" density. For example, the density at the surface to be hardened might be as high as 7.5 g/cm^3 or even higher, and it gradually decreases to a base density

Fig. 2: Variations of the Inductoscan family of advanced induction equipment for heat treating powder metallurgy parts (Courtesy of Inductoheat Europe GmbH, an Inductotherm Group company)

of 7.0–7.2 g/cm^3. This helps maximize beneficial compressive residual stresses at the surface, further improves fatigue strength and load-carrying capacity. It is particularly critical to avoid having sharp corners/edges on P/M parts within regions required to be induction hardened. Sufficient chamfering and radii should be applied.

When determining process parameters for induction hardening of P/M parts, energies and frequencies higher than those used for wrought equivalents are often needed. Closer process control is also required. Preheating and/or pulse heating might be beneficial for proper austenization when hardening complex geometries.

It is quite common for P/M materials to absorb appreciable amount of oil. Therefore, sufficient ventilation must be incorporated into machine design. It is also imperative to make sure that steps are taken to ensure that the reusable quenchants remain sufficiently clean and maintain appropriate cooling characteristics when running high production.

The P/M industry continues to improve its technology. In the past, P/M parts sometimes were tagged “low strength”. The low strength and high porosity of P/M parts held back the widespread adoption of induction hardening. Not anymore. Improvements in manufacturing of P/M parts and greater awareness of specifics of induction hardening of P/M parts have further emerged in recent years. A number of different tools (including numerical computer modeling) are now available to develop intelligent process protocols as well as highly efficient and flexible equipment that will ensure success in induction heat treating of P/M components. As an example, **Fig. 2** shows three variations of the Inductoscan family (Inductoscan Move, Inductoscan Platinum, Inductoscan Flex) of advanced induction equipment that are quickly becoming a new industry standard for heat treating powder metallurgy parts.

LITERATURE

[1] Rudnev, V.; Loveless, D.; Cook, R.: Handbook of induction heating. 2nd Edition, CRC press, 2017

AUTHOR

Dr. **Valery Rudnev**
Inductoheat Inc., an Inductotherm Group company,
Madison Heights, Michigan, USA
+1 (0)248 / 629-5055
rudnev@inductoheat.com