INDUCTION HEATING
HELPS PUT WIND TURBINES IN HIGH GEAR

Accurately controlled induction heat treating systems can selectively harden specific areas of gear teeth and bearing races producing the required metallurgical properties with minimum shape distortion, providing high quality parts that directly affect the longevity of wind turbines.

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Wind is an inexhaustible source of energy that is not affected by fuel price instability and it is free of CO_2 emission (Fig.1). According to a report from the American Wind Energy Association (AWEA), in 2008, with over 8,500 MW installed, wind power provided 42% of all the new generating capacity added in the U.S.[1]. A 2008 report by the U.S. Department of Energy (DOE) predicts that by 2030 wind energy could generate 20% of the nation's electricity.

Since most wind turbines are constructed on remote sites, the size and weight of turbines in combination with the expenses associated with their repair demand superior strength, and higher quality of wind energy-generator components. Therefore, the quality of case hardened large gears and raceways (single or double) directly affects the longevity of wind turbines and their competitiveness.

For over 30 years, Inductoheat has been providing industry with high-quality, repeatable, and accurately controlled induction heat treating systems, which can selectively harden specific areas of gear teeth and bearing races producing a fine-grain martensitic layer with minimum shape distortion. The remainder of the part is unaffected by the induction process. Hardness, wear resistance, contact fatigue strength, and impact strength increase, which help to eliminate premature gearbox failure. Another goal of induction gear hardening is to produce considerable compressive residual stresses at the surface and in a subsurface region[2-4]. Compressive stresses help inhibit crack development and resist tensile bending fatigue.

Induction hardening of large gears

Gear performance characteristics (including load condition and operating environment) dictate the required surface and core hardness, hardness profile, residual stress distribution, grade of steel, and the prior microstructure of the steel[2-4]. In contrast to carburizing and nitriding, induction hardening does not require heating the whole gear or pinion. With induction, heating can be localized to only those areas requiring metallurgical changes. For example, the flanks, roots, and

Fig. 1 — Wind energy is an inexhaustible green source of energy.

Fig. 2 — Tooth-by-tooth induction hardening can be applied to external and internal large gears and pinions requiring the inductor to be symmetrically located between two flanks of adjacent teeth.

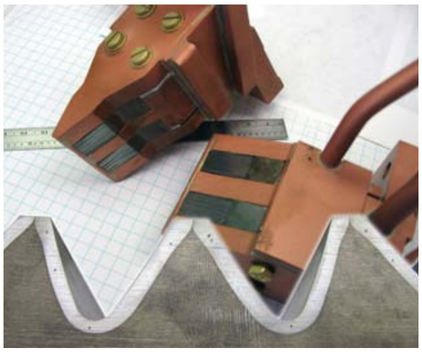

Fig. 3 — In tooth-by-tooth hardening, inductors can be designed to selectively harden specific areas of gear teeth where metallurgical changes are required (e.g., root, fillet and/or flank of the tooth) producing a fine-grain martensitic layer with minimum shape distortion. The remainder of the part is unaffected by the induction process maintaining its toughness and ductility.

Fig. 4 — Induction gear-hardening machine for a large bearing ring for a wind-turbine generator with teeth located on the inside diameter of the ring. The bearing ring OD can be as large as 140 in. (3,500 mm). The required case depth is 2.5 to 3.5 mm, the *z*-axis scan height (tooth width) is 13.75 in. (350 mm), and the maximum weight exceeds 11,000 lb (5,000 kg).

tips of gear teeth can be selectively hardened.

The tooth-by-tooth hardening concept is the most suitable for induction hardening large gears instead of a spin hardening technique. In the latter technique, the gear is encircled by the induction coil, which requires a substantially greater amount of power and capital equipment investment due to the necessity of heating the bulk mass of metal of the large gear all at once.

The tooth-by-tooth hardening concept can be applied to external and internal gears and pinions, and it requires the inductor to be symmetrically located between two flanks of adjacent teeth (Figs. 2 and 3). There are many variations of coil designs used to apply this principle to an almost endless variety of gear types, tooth profiles, and sizes. Inductors can be designed to heat only the root and/or flank of the tooth, leaving the tip and tooth core soft, tough and ductile (Fig. 3). Induction-hardened gears can be fairly large with outside diameters easily exceeding 100 in. (2.54 m), and can weigh several tons.

Typically, the inductor-scanning mode is used for tooth-by-tooth hardening gears with wide faces. Two scanning techniques used include one where the inductor is stationary and the gear is moveable, and the other where the gear is stationary and the inductor is moveable.

Tooth-by tooth induction gear hardening

As an example, Fig. 4 shows a tooth-by-tooth induction gear-hardening machine for a large bearing ring for a wind energy turbine with teeth located on inside diameter of the ring. A bearing ring OD can be as large as 140 in. (3,556 mm), and the maximum weight exceeds 11,000 lb (5,000 kg). The required case depth is 2.5 to 3.5 mm. The *z*-axis scan height (tooth width) is 13.75 in. (350 mm).

Precise inductor fabrication techniques, inductor rigidity, and superior alignment techniques are required. Special locators or electronic tracing systems are often used to ensure proper inductor positioning in the tooth space. Thermal expansion of metal during heating should also be taken into consideration when determining the proper inductor-to-gear tooth air gap. After ring loading and initial coil positioning, the process runs automatically based on an application recipe.

When developing tooth-by-tooth gear hardening, particular attention should be paid to electromagnetic end/edge effects and the ability to provide the required pattern in the gear end areas, as well as along the tooth perimeter. To obtain the required temperature uniformity, it is necessary to use a complex control algorithm: Power and Scan Rate vs. Inductor Position, which has been well developed by this group.

With tooth-by-tooth induction hardening, the shape/size distortion is mainly noticeable in the last heating position with the last tooth being pushed out. Hardening every second or third tooth can dramatically minimize distortion. Obviously, this will require two to three revolutions to harden the entire gear.

Carburizing operations require soaking of gears for many hours (in some cases up to 30 hours or longer) at temperatures of 850 to 950ºC. At these temperatures, the large masses of metal expand to a much greater extent compared to a situation where only the gear surface layer is inductively heated. The expansion of a large mass of metal during heating/soaking and its contraction during cooling/quenching after carburizing results in much greater gear shape distortion compared with the distortion after induction hardening, which requires time-consuming finish grinding.

One of the challenges with tooth-by-tooth hardening is related to the appearance of undesirable heating of the areas adjacent to the hardened area (tempering back effect). There are two main reasons why an undesirable tempering back can take place[2-4].

The first deals with the external magnetic field coupling phenomena of the inductor[4].

The second is related to thermal conductivity phenomena. Heat is transferred by thermal conduction from a high-temperature region of the gear surface toward its lower-temperature region. During hardening, the surface temperature exceeds the A_{c3} temperature. Therefore, when heating one side of the tooth, there is a danger that the opposite side of the gear tooth will be heated by thermal conductivity to an inappropriately high temperature, which will result in undesirable tempering back of previously hardened areas of the tooth.

Whether a hardened face of a tooth

will be softened due to tempering back mainly depends on the applied frequency, gear module, tooth shape, heat time, and hardened case depth. In the case of shallow and moderate case depth and large teeth, the root of the tooth, its fillet, and bottom of the tooth flank typically are not excessively heated because the massive area below the tooth root serves as appreciable heat sink, which helps to conduct excess heat and protects the previously hardened side of the tooth from undesirable tempering back.

To overcome the problem of tempering back, special cooling spray blocks are applied. Additional cooling protects already hardened areas while heating unhardened areas of the gear. Even though external cooling is applied, there still may be some unavoidable tempering back depending on the tooth shape and process parameters. This tempering back is typically insignificant, well controlled, and acceptable (Fig.3). In some cases, a submerged induction hardening technique is used[4].

Induction hardening of raceways

Similar to gear hardening, there are two basic approaches to inductively heating large raceways, namely a single-shot (static) hardening process and a scanning process.

Single-shot gear hardening: In static induction heating, the ring is surrounded by a single-turn or multi-turn solenoid coil. For example, to harden the surface of the inside diameter of a bearing race, an induction coil is positioned inside of the ring. However, if it is required to have a heat treated hardness layer on the outside diameter of the ring, then induction coil is placed around its outside diameter encircling the ring being heated. The ring may be rotated (spun) during the heat treatment process to ensure an even distribution of energy along its perimeter over the entire heating cycle. Upon completion of the heating stage, the ring is lowered into a separate concentric spray quench device positioned below the inductor and spray-quenched in-place, or it is submerged in a quench tank and quenching takes place inside the tank while the quenchant is usually agitated. Single-shot hardening is best for smaller gears to minimize coil and power-supply costs.

Scan hardening: In induction scan hardening, a short inductor moves (scans) along a circular path concentric with the ring (along the ring's periphery). A spray quench block (quench jet) follows the inductor, or is incorporated into the inductor design. This method requires significantly less power than the singleshot process since only a small portion of th ering is consequently heated.

Fig. 5 — InductoScan base compact machine for bearing ring induction scan hardening. Rings are loaded into position by crane. Scan hardening is managed using Siemens 840D control.

As an example, Fig. 5 shows and InductoScan™ base compact machine for bearing-ring scan hardening. The transformer is mounted on a spring-loaded *x-y* slide. Rings are loaded with a crane into the load position, and the component is moved into the hardening station where it is moved against the coil (which is equipped with guides). Thus, a precise coupling distance is ensured for the entire hardening process. The part then rotates for scan hardening via a circular axis. The heated portion of the ring is spray quenched during the scan hardening. The scan rate is 0.5 in./s (12 mm/s). The outside diameter of the bearing ring is up to 55 in. (1,400 mm), and the typical case depth is about 0.100 to 0.120 in. (2.5 to 3 mm).

Scan hardening of raceways using a single inductor is simple and the most economical approach requiring minimum capital cost and using the simplest control and machine design. However, a narrow soft band (transition zone) is inevitably created with this technique due to the tempered back effect of the region adjoining the final ring section to be heated. Special techniques were developed to minimize the length of the transition zone. In some cases, an angled band is preferable instead of a straight transition band.

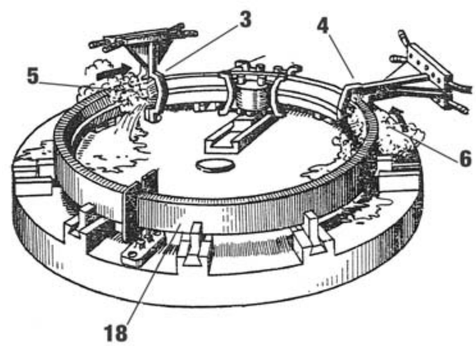

Fig. 6 — Process concept that allows eliminating soft spots by using two scanning inductors (adapted from Ref. 5).

To prevent the occurrence of the tempered back soft zone without the necessity of using an unduly large, expensive power source, an alternative process has been developed. In the method (Fig.6), instead of using a single inductor, a pair of heating inductors is used (Nos. 3 and 4 in Fig. 6). At the start of the heating process, identical power is supplied to both inductors while each inductor travels in an arc of a little less than 180 degrees in opposite directions at a uniform speed. Trailing each inductor is a corresponding quench jet incorporated into each inductor, or separate quenching blocks (Nos. 5 and 6 in Fig. 6), until the inductors meet again at the end of the heating process in the final heating position, where they are deenergized and, simultaneously, an auxiliary quench is automatically applied to quench the final heated portion of the ring. The adjacent inductors complement each other's magnetic field in the final heating position eliminating any soft zones caused by undesirable temper back when a single scan inductor is used.

The description of the process concept that allows eliminating soft spots using two scanning inductors (Fig.6) was adapted from the Russian literature[5] published in the late 1970s. In fact, this was not the first description of scan hardening that eliminates soft spots using two independently moving heaters. Other descriptions can be traced back to the early 1940s[6-9]. For example, Fig.7 was adapted from a patent issued in the early 1960s[6].

In its continuing tradition to significantly improve on existing technologies, Inductoheat recently developed novel technology (patent pending) that further perfects the known general process of eliminating soft spots when hardening large ring-shaped parts using two independently scanning inductors[10]. The technology uses numerous know-how specifically developed to meet the need for induction case hardening of wind mill components.

Some innovations are related to unique ability of Inductoheat's inverters to independently control power and frequency during the scanning operation, which helps to optimize thermal conditions at initial and final scanning stages. Other features are related to process subtleties and recipes, as well as effective handling of large-sized parts. **HTP**

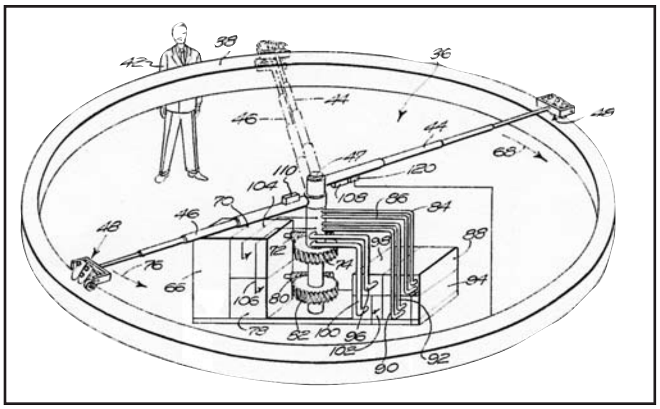

Fig. 7 — One of the earliest descriptions of surface hardening of large ring-shaped components using two independently scanning heaters without soft spot (adapted from Ref. 6).

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