"Go hard into the Wind" – Induction hardening of large rings for wind turbines

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Wind power, particularly through the growth of offshore wind installations, will play a leading role in our renewable energy future. Cost-effective offshore energy production requires virtually maintenance-free wind turbines, posing a special design challenge for highly and dynamically loaded components such as rotary joints and bearing rings. The preferred manufacturing method for reliably creating hard, wear-resistant component surfaces is induction hardening. The surface material's metallurgical structure is transformed (hardened) through a well-controlled sequence of induction heating and rapid cooling (quenching).This process is used, for example, to harden ring gears, slewing rings, and bearing races. Different hardening system designs are available for optimum and reproducible results. The most flexible hardening system features a work piece tilt table to optimize quenching fluid flow to the bearing raceways and/or gear teeth. Additional patented SMS-Elotherm technologies such as work piece net power monitoring and automatic inductor position control combine to make induction hardening a robust and precise manufacturing process that is easily integrated into existing production lines.

Today wind energy supplies the electrical power requirements of almost 8 million households. Plans call for wind power to produce 25% of Germany's electrical energy by 2025. About half of this power would come from installations located far off-shore. Winds on the open seas are generally stronger and more continuous, offering up to 40% higher power output compared to winds on land. However, the repair and maintenance on the high seas is more involved and expensive. Induction-hardened components increase system wear resistance and minimize service costs for off-shore wind turbines.

Where is induction technology used in wind turbines?

Wind turbine bearings must have a maintenance free service life of at least 20 years. Particularly harsh demands are placed on the large roller bearings for the rotation of the nacelle azimuth (yaw), the main rotor, and the blade pitch adjustment. These critical bearings and associated gearing can be hardened for improved strength and wear resistance. Induction technology provides a fast, energy-saving hardening process with excellent and reproducible results.

Characteristics of various surface hardening techniques

Table 1 compares the attributes of the various surface hardening technologies used to improve the properties of large roller bearing rings.The precise process control offered by modern induction systems produces uniform and highly reproducible surface hardening. The high degree of induction process automation yields consistently superior quality day after day, month and month, year after year.

Induction principle

The inductive surface hardening process is governed by Faraday's Law of Induction. The changing magnetic field induces an electrical voltage. This voltage causes an electrical current flow in an electrically conductive material, thereby heating the material. By the "skin effect" the heat input decreases with increasing depth into the work piece. The effective heating depth can be influenced by adjusting the frequency of the magnetic field used to drive the induction process. The material to be hardened is heated to the austenitizing temperature and then rapidly cooled (quenched), causing the formation of a hard surface case including a very hard material called martensite.

Gear tooth hardening

Gear teeth on the inner or outer diameter of large roller bearing rings are also hardened with induction. Typically the tooth base and flank are hardened, and a "soft zone" (unhardened region) is maintained at the tooth tip. The induction frequency ranging between 4 kHz and 30 kHz is selected to achieve the desired case depth. High throughput production systems are capable of processing multiple teeth simultaneously (**Fig. 1** and **2**).

Bearing raceways

Three process techniques are used to inductively harden roller bearing raceways:

1. Scan hardening with a soft zone
2. Scan hardening with no soft zone
3. Single shot hardening with no soft zone

Scan hardening with a soft zone

Scan hardening with a soft zone is the standard process for raceway harden-

Table 1: Surface hardening technology

Surface Hardening Technologies:

Induction Hardening	Flame Hardening	Carburizing	Nitriding
• Uniform heating of the areas to be hardened • Short heating times (reduced scale build-up, no formation of large grain structures) • Little or no machining required after hardening (minimal part distortion) • Reliable control of heat input and part temperature • Partial hardening possible – even with complex part geometries • Inductors adaptable to virtually all part geometries • Very large and massive parts can be hardened • Easily integrated into new and existing production lines • Small equipment footprint • Simple, straightforward operation and high reliability • Environmentally friendly (reduced energy consumption and CO_2 emissions)	• Short heating times • Little or no machining required after hardening (minimal part distortion) • Partial hardening possible • Small equipment footprint • Simple, straightforward operation • Temperature errors due to variation in gas pressure and flame positioning • Poor hardening depth reproducibility • Different burners needed for individual parts	• Thin, but uniform hardening depth • Partial hardening possible • High operating costs, high energy consumption • Long annealing times • Prone to large part distortions • Shielding required for surfaces that should not be hardened • A centralized hardening facility is required (transport and logistic costs) • Post processing (part cleaning) is required • Hardness and hardness case depth falls-off at the base of the tooth for large gears.	• Due to reduced hardening capabilities the suitability of nitriding for large ring hardening applications is limited.

ing. The inductor assembly includes a quenching shower head and is mounted on a linear axis to compensate for a range of different ring diameters. The inductor assembly remains stationary during the hardening process, except for small movements required to maintain the correct standoff distance between the inductor and the ring. The ring rotates with a low, constant tangential velocity past the inductor. For thicker (e.g. 6 mm or more) case depths the work piece is inductively preheated before final heating to the austenitizing temperature. A small soft zone (unhardened area) remains at the end of the scan path.

Fig. 3 and **4** show two different induction scan hardening machines. Both machines are capable of hardening raceways and gear teeth on the inner and outer ring diameters. The machine in Fig. 4, however, features a tilt table to orient the work piece for optimal quench control for different hardening applications. For gear tooth hardening, a horizontal work piece is preferred. For raceway hardening, a tilted or vertical ring works well.

The flexible automatic tilt machine shown in **Fig. 5** performs horizontal, vertical, and tilted scan hardening. Industrial hardening machines for work piece diameters up to 6 m (20 feet) and weights up to 20 tons are reliably working in high throughput production settings.

Scan hardening with no soft Zone

The SMS-Elotherm patented process for inductive scan hardening [1] with no

Fig. 1: Single tooth hardening

Fig. 2: Finish hardened teeth

Fig. 3: Model ZHM induction hardening machine, horizontally positioned ring

soft zone begins with inductive heating of a start-position by two scanning heads. Each scanning head operates independently with its own inductor coil, quenching spray, and servo motion control. After initial heating at a common start position, both heads travel along the work piece surface in opposite directions, heating and then quenching the surface as they move. At the opposite side of the work piece the two hot zones come together and are quenched with a stationary spray fixture, producing an inductively hardened work piece with no soft zone. This technique of using dual independent scanning heads provides a cost-effective solution for hardening even the largest work pieces with minimal peak input power requirements (**Fig. 6**).

Complete surface hardening with no soft zone

In this process the work piece rotates at high speed past one or more stationary inductor(s). After multiple rotations the work piece surface reaches the required temperature and the entire surface is quenched. This complete surface hardening technique is well suited for smaller diameter work pieces. The costs for the system, factory space, input power, and cooling grow quickly as the work piece diameter increases (**Fig. 7**).

Fig. 5: Model RHM-S induction hardening machine with pre-heater & 0-70° adjustable tilt table

Fig. 4: Model RHM induction hardening machine, stationary tilted ring (70°)

Double row ball raceway hardening

For hardening double row ball and roller raceways (for example in large slewing rings) the use of a twin inductor is particularly interesting, as the hardening process productivity is essentially doubled. When coupled with a suitable power supply, the SMS-Elotherm twin inductor scan hardens both raceways simultaneously. **Fig. 8** illustrates a typical twin inductor design.

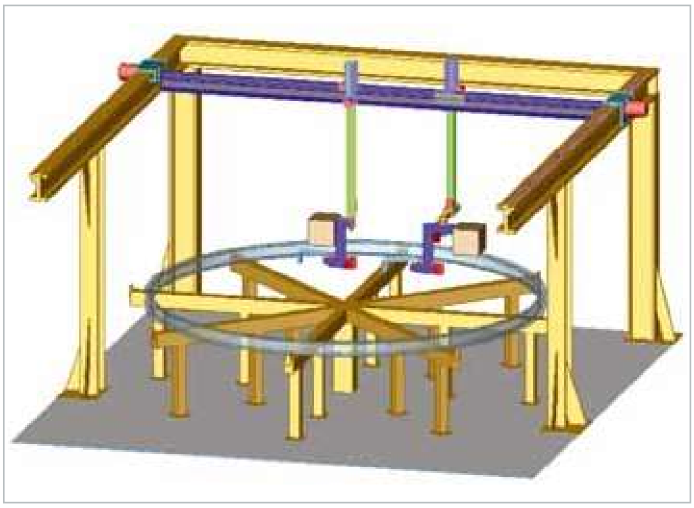

Fig. 6: Machine for ring hardening no soft zone (concept illustration)

Fig. 7: Model UVH induction hardening machine, horizontally positioned ring

With single head induction hardening there is always a risk that the previously hardened raceway will be softened (annealed) when the adjacent raceway is hardened. The twin inductor process eliminates this risk. Moreover, the trend toward compact (thin) slewing rings with increased hardness case depths leads to narrowed shoulders between the raceways. The narrowed shoulder designs are prone to complete through-hardening, which is usually an unwanted side effect of traditional hardening methods. The patent-pending SMS-Elotherm twin inductor design reliably prevents this problem. **Fig. 9** shows the numerical simulation for the formation of the austenitized region (gray area). Unwanted through-hardening of the raceway shoulder is avoided. With supplemental shoulder cooling the twin inductor can be used for high throughput hardening of very thin shoulder double row rings (**Fig. 10 a/b**).

Work piece net power monitoring for on-line hardening quality control

In addition to normal machining tolerances, thermal distortion during raceway hardening contributes to work piece dimensional variations. Inductor positioning control systems have been implemented to compensate for these variations during the hardening process. Residual inductor positioning errors during the hardening process, however, still cause significant errors in the final case depth and quality. Conventional hardening tools have not been able to assess these hardening errors in real time. With increasing bearing load and service life requirements, these residual errors are no longer acceptable. Continuous online measurement of process parameters is required to monitor the hardening process in real time. The influence of inductor position on electrically measurable signals, particularly the converter (power supply) power, is observable even on conventional induction systems. The useful signal strength, or measurement sensitivity, however, is very low.

By contrast, the SMS-Elotherm patented *work piece net power monitor* [2] provides robust feedback for online quality control. Previous power measuring methods relied on phase-corrected multiplication of converter current and voltage. The validity of the resulting measurement signal was compromised by the inclusion of irrelevant wasted power that did not contribute to work piece heating. The SMS-Elotherm *work piece net power monitor* filters out this irrelevant wasted power. The resulting monitor signal reflects the real net power to heat the work piece as part of the hardening process.

Fig. 11 illustrates how the two different power signals (converter output power and work piece net power) vary in response to changes in the inductor standoff distance. Note how the converter output power signal has poor sensitivity to changes in the inductor position. The *work piece net power monitor,* however, provides easily recognizable signal changes in response to small inductor position variations. The *work piece net power monitor* works like a magnifying glass, revealing net power losses that would otherwise be masked by losses in the resonant induction circuit. Using this "magnifying

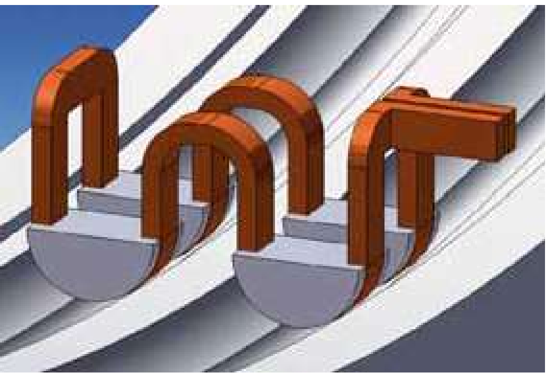

Fig. 8: Twin inductor (Illustration)

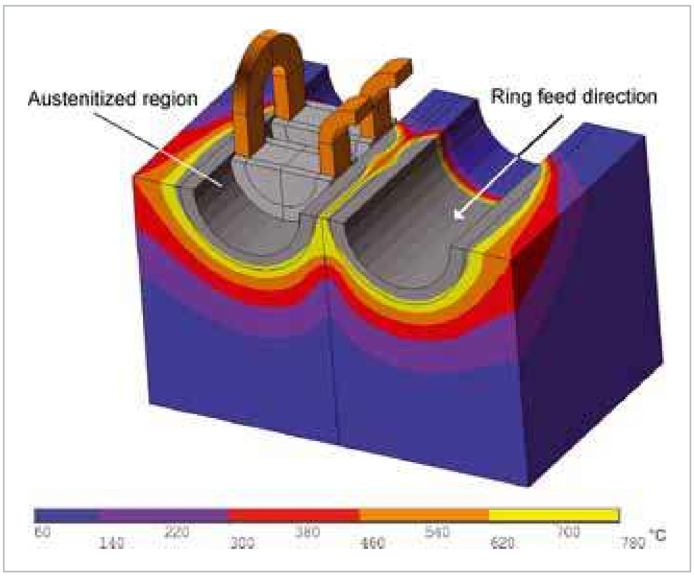

Fig. 9: Finite element temperature model for a Twin Inductor

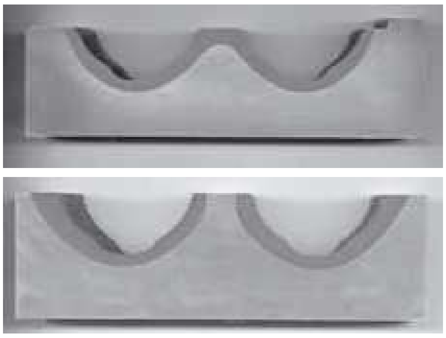

Fig. 10: Optimized Twin Inductor raceway hardening for thin, double-row slewing rings

Fig. 12: Non-contact sensor for automatic inductor position control

glass effect" even the smallest irregularities and inductor position errors can be recognized and located on the work piece surface.

Non-contact automatic inductor position control

The patented SMS-Elotherm *automatic inductor position control* [3] senses and corrects inductor position errors in real-time during the hardening process. Simultaneously, the *work piece net power monitor* provides continuous online quality control. Result: consistent and reproducible surface hardness and depth, leading to higher load capacities and longer service lives for large roller and ball bearings (**Fig. 12**).

Outlook

The hardening process is critical to assure the component properties and wear resistance needed in modern wind turbine rotary joints. Induction hardening technology is particularly useful in these applications. Induction process tools are operationally straightforward for reproducible, high-quality results. Moreover, induction provides flexible, cost-effective, and energy-efficient hardening of simple and complex parts, both large and small.

Induction hardening already plays a critical role in the successful build-out of renewable wind power, particularly offshore wind power. Improved induction hardening capabilities are already emerging to meet new challenges. Additional productivity improvements will be realized through scan optimization and the reduction of non-process time. The induction technology roadmap also looks forward to inductive hardening of ever more complex and compact geometries incorporating targeted soft zones for higher component fatigue strength.

Literature

[1] SMS Elotherm Patent DE 10 2006 003 014 B3, Process for hardening a closed curve shaped work piece

[2] SMS Elotherm Patent EP 0 427 879 B1, Device and process for inductive heating of a work piece

[3] SMS Elotherm Patent DE100 34 357 C1, Process and device for heating work piece surfaces

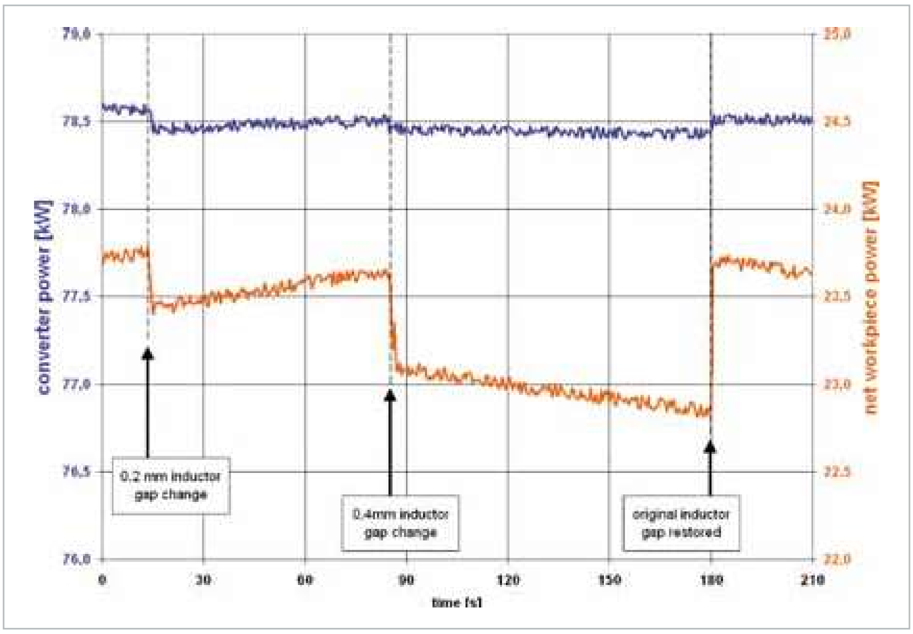

Fig. 11: Influence of inductor position on converter power and work piece net power

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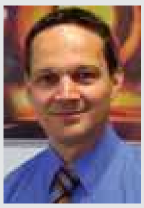

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