INDUCTION HARDENING OF GEARS OFFERS VARIOUS APPROACHES

Fast, clean, highly repeatable, and inexpensive when properly sized for the job, induction heating offers a desirable production solution for gear hardening regardless of part size and geometry.

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Induction hardening offers a practical alternative technique to thermochemical methods such as carburizing or carbonitriding to improve the mechanical properties of gears. Advancements in gear materials and the development of new induction heating simulation and prediction tools have led to improved induction systems that extend the induction hardening process capability to include very demanding gear configurations. This article describes the various induction processes for hardening gears.

Hardening methods

Interest in using induction hardening of gears continues to increase as process capabilities advance with the development of larger power sources for manufacturing facilities. At the same time, users want faster and more flexible and repeatable hardening solutions. Hardening with or without specific tooling were the two main methods for hardening. Hardening methods using quench tooling include an operation using a specific tool and an operation under a quench press (die quenching).

Hardening under a quench press (die quenching) is used when very strict tolerances are required in the part design and need to be obtained after the hardening operation. The best approach is to use a press with specific dies. Depending on part design and accuracy requirements, the press can use single or multiple dies (Fig. 2).

The balance of the article will review other gear hardening technologies, focusing on whole gear hardening processes.

Induction hardening can meet production needs in processing a range of gears designs, from small sprockets to very large gears used in transmissions. Two main concepts are to harden only the gear tooth or part of it (only where the tooth makes contact, for example) and to harden the entire gear circumference including the tip and root of each tooth (Fig. 3). Other considerations such as gear size, module, production rate, power availability influence the choice of the process.

Tooth-by-Tooth Hardening

This technique is commonly used to harden flanks and roots; for example, large sprockets such as those found in off-road equipment, or ring gears found in transmissions. In the process, the coil comes onto the tooth to harden root and flanks, or flanks and tip. Possible approaches are single shot and scanning operations. Some processing, such as the so-called NATCO approach, performs the hardening operation under water, which minimizes the distortion resulting from the transformation.

A current method used for large gears (e.g., slewing rings) uses more...
measuring devices, which make it possible to guarantee a perfect location of the coil vs. the part even when part is not well centered. This also provides the necessary process repeatability.

The air gap between coil and tooth must be constant during the heating process, but more important is the repeatability of positioning from one tooth to another. To achieve regular control using measuring probe, a CNC axis gives the best result. Other solutions used to ensure a constant gap between coil and tooth flanks and/or root include mechanical when using a contact probe in neighboring teeth and ground-fault detection in connection with the control system (CNC or PLC) giving a set point when approaching the root of the tooth.

**Gear Spin Hardening**

In spin hardening, the entire gear is brought up to the austenitizing temperature via an encircling coil and subsequently quenched, which allows either through hardening of the gear down to the tooth root (similar to case hardening) or hardening the outer surface at a uniform or irregular distance from the face. Figure 4 shows different methods for contour hardening corresponding to different heating techniques for inductive gear spin hardening.

**Through Hardening on Gear Teeth**

For gears that are predominantly subject to wear (e.g., sprockets), the tooth is through hardened using a relatively low specific power \[^2\]. If the frequency is too low, there is the risk that beyond the Curie temperature (point where the material changes from magnetic to nonmagnetic) the induced eddy current largely flows only in the root circle, and the temperature of the tooth lags behind.
Quenching for through hardening can be either submersion or spraying depending on the material [3]. Depending on factors from the module to the frequency, it is recommended to delay the quenching sequence to achieve a uniform temperature between the tooth and the root circle. Tempering after through hardening is essential for crack prevention. An example of a submerged hardened gear is shown in Fig. 5.

**Gear Hardening on Tooth Perimeter (Contour or No Contour)**

When hardening at an irregular distance from the tooth face, or (ideally) at a uniform distance from the tooth face, one can choose between the single frequency concept (SFC), in which an single frequency power supply is used, and the dual frequency method (including multiple frequency concept, or MFC) using two frequency levels (either simultaneously or not).

**Single Frequency Concept**

In the process, the inductor is fed from a single power supply using a frequency selected according to the module. Heating (austenitizing) is done either via single shot in one step or with preheating using reduced power to reach a temperature between 550 to 750°C (1020 to 1380°F) and subsequent final heating using a higher specific power to the hardening temperature. Preheating can also consist of several pulsed cycles. The purpose of preheating is to reach an adapted high austenitizing temperature in the root circle during final heating, without overheating the tooth tip. The schematic principle can be seen in Fig. 6. To achieve hardening profiles at an irregular distance from the tooth face using a single frequency, short heating times combined with a high specific power is usually required. Both parameters (time and power) depend on the hardened gear module.

It is not always certain that the user has the optimum power supply with respect to available frequency, or whether it can be correspondingly adjusted. In this case, better results can be achieved for contour hardening using a generator in which the working frequency is higher rather than lower for the given module.

If the frequency is higher than in the ideal case, it is possible to heat the root circle by means of thermo-conduction during the preheating phase to subsequently achieve hardening results at an irregular distance from the face with a final heating impulse using a high specific power (Fig. 7). On the other hand, if the generator frequency is too low for a given module, through hardening of the tooth or an inadequate austenitizing temperature of the tooth tip is unavoidable for physical reasons. In addition, if the initial microstructure is not suitable for gear hardening, further improvement in the hardening result may be achieved via induction initial hardening and tempering operations before the actual hardening itself. For this, heating of the entire gear area to an austenitizing temperature corresponding to the material is carried out. Cooling by self-quenching (mass quenching) is followed by a short inductive tempering of the entire gear. The actual hardening zone at an irregular distance from the face is then generated by a short final heating. The schematic time-temperature graph for single frequency contour hardening, prehardened, and tempered by induction, is shown in Fig. 8.

**Dual-Frequency Methods**

Dual-frequency hardening using separate frequencies allows achieving hardening profiles similar to those achieved using case hardening. Two different frequencies, one after the other, are applied to the gear. The tooth part is preheated (depending...
on the material) using a low frequency and limited power to a temperature between 550 and 750°C. The frequency should be such that the preheating preferably takes place in the root circle region. After a short delay, austenitizing using a higher frequency and higher power density is then provided. Heating times are measured in tenths of seconds or seconds (depending on the module and gear thickness/length) in this final heating phase, and requires then a very accurate, fast monitoring system [5]. Figure 9 illustrates this process, and Fig. 10 shows a hardened gear using two separate frequencies.

Due to the requirements of material hardenability in the contour hardening process, prequenching and tempering by induction of the tooth area prior final hardening may be considered as an alternative process (just as in the case of the single frequency contour hardening process). This process is illustrated in Fig. 11.

**Simultaneous Frequency Hardening**

In this method, a lower medium frequency (MF) and a higher (HF) frequency are fed in the inductor simultaneously. This is accomplished using two inverters and feeding a single coil using proper filtering devices, avoiding rejection of frequencies and perturbations within the electrical circuits (Fig. 12). Such system envisioned in the mid 1920s was patented by EFD Induction in 1992 (ELVA patent) using the advantages of transistor power supplies. Figure 13 shows a gear being processed using MFC.

Preheating, which is necessary in the normal dual frequency method using separate frequencies, is not used [6]. Dual-frequency contour hardening using simultaneous frequencies is done by heating in the region of the root circle by means of the MF, and in the tooth tip region using the HF (Fig. 14). However, the short heating times required in this process place higher demands on the generator and machine engineering. An example of a hardening profile which can be achieved using this method is shown in Fig. 15.

The MFC process is suitable when the use of simultaneous frequencies is necessary, such as in the bevel gears having small to medium size module. It is also very suitable when material and final metallurgical structure required by the end-user allows using a short heating time (Fig. 16).
Quenching

Quenching from the austenitizing temperature can either be done using a spray head or by (turbulent) submerge quenching. Quench media must be compatible with the gear material. Quenching has a considerable importance for perfect hardening results in gear spin hardening, at both a uniform and an irregular distance from the face. It should be performed directly after final heating with as little delay as possible (fast CNC axis for positioning the spray head, or quenching from the inductor via an integrated quenching circuit).

During the quenching phase, the rotational speed of the gear is decreased from approximately 600 to 800 rpm (the speed during the heating phase) below 50 rpm to avoid a shadow effect on the flank opposing the direction of rotation, but also to avoid incomplete transformation in the gear root with creation of bainite due to a too slow quench speed.

In addition to factors specific to the method (such as frequency and power), there are many other process relevant factors that influence the hardening result in the gear spin hardening of gears including part material and initial microstructure, part dimensions and shape, distortion, and fatigue and stress.

Materials and Initial Structure

In principle, all steels typically recommended for induction hardening can also be used in gears for induction hardening, although the carbon content should not be below 0.45% for unalloyed grades. Due to the short austenitizing times required, the initial structure of the steel is also of considerable importance, having to be close-grained with a grain size index of ASTM 7 (6) or higher (i.e., finer structure). A hardened and tempered (Q + T) prior structure offers the best starting point.

Unsuitable microstructures are inhomogeneous pearlite-ferrite initial structures. The smaller the module, the more important are the initial structure and carbon content, and, thus, the required austenitizing temperature (i.e., with unsuitable material parameters, it is more likely that undesired through hardening will occur than with optimal qualities). If a somewhat increased quenching distortion is acceptable, the above-described prequenching and tempering by induction of the gear part can make a marked improvement on the hardenability of critical structures using the same hardening equipment, and before the contour hardening itself.

Gear Dimensions

The suitable module range is (1.8) $2.2 < m \leq 5$ mm for the dual-frequency method using simultaneous frequencies. The gear diameter suitable for this method should be limited to approx. $d \leq 250$ mm for economic reasons even if the equipment is already in place, because in view of the short heating times, the MF power especially may be proportionally high (60 to 65 % of the total power). It is important to understand that short heating times mean high power density as shown in Fig. 17. The phenomenon is even more important when considering simultaneous heating process of a two frequency level (MFC technique).

For modules where $m \leq 3.0$ mm, the separate dual-frequency method using subsequent MF and HF energy application is, in part, better than the simultaneous dual-frequency method, as here (assuming an adequate energy density) the best opportunity for a hardening at an irregular distance to the face is offered using HF final hardening alone. It is advantageous if the energy source permits
adaptation of the final heating frequency for the size of the gear. If a slight loss of uniformity in the distance from the face is acceptable, for modules where \( m \leq 3.0 \text{ mm} \) it is likewise possible to carry out the preheating using the same high frequency required for the final heating. The loss of middle frequency energy in this case has economic advantages. However, it is very important to note that the specific power required avoiding through hardening significantly increases with ever smaller teeth. The single frequency method is almost exclusively used for internal ring gears having a module where \( m \leq 1.25 \text{ mm} \), such as those frequently used today in automotive automatic transmission systems (splines more than gears). Despite using a frequency, \( f > 150 \text{ kHz} \), a complete through hardening of the gear occurs.

**Gear shape**

Spur-toothed and helical spur gears and internal gears can be hardened at a regular or an irregular distance from the face. In the case of helical gearing, an asymmetrical hardening (off-set patterns) of the tooth flank at a depth of up to approximately 2 to 3 mm measured from the faces of the gear has to be accepted (the tip exit flank is hard-ened from the faces of the gear has to be approximately 2 to 3 mm measured to tooth flank at a depth of up to approximately 2 to 3 mm measured from the faces of the gear has to be accepted (the tip exit flank is hardened to a greater depth)\(^7\). However, this situation is only more pronounced from a helix angle of \( b \geq 28 \) degrees (Fig. 18). Patented coil solutions enhancing power distribution can limit this effect. Gears that have functional zones to be hardened in addition to the teeth are, as a rule, less suited to inductive contour hardening (several inductors, mountings, and working steps may be required, tempering of the initially hardened zone is possible).

**Distortion**

As is the case with any heat treatment that has the goal of a martensitic case, inductive contour hardening causes dimensional changes to the workpiece regardless of heating time. However, usually only slight distortion is expected compared with that of furnace hardening due to the small heated mass compared with the overall mass of the workpiece. If the gear body is favorably formed, processing of the workpiece can be completed. In critical cases, hardening trials on an adequate number of test pieces must be performed to determine the average expected distortion. If the starting conditions remain the same (material composition, initial microstructure, and internal stresses), the resulting quenching distortion when using induction hardening will be similar, but with less variance.

The MFC technique was developed to avoid distortion when considering gear hardening process. Nearly 15 years after having introduced the technology, we know that there is no way to completely avoid the distortion resulting from the modification of the condition of the part and the release of the residual stresses in the part from the manufacturing process.

**Fatigue and Stress**

The designer wants to achieve certain mechanical properties in the part such as high wear resistance and fatigue strength via part hardness and case depth. The user wants compressive stresses in the gear root and flank. Too much difference between both areas can create a risk for crack initiation and gear failure (Fig. 19). Experience in gear hardening has demonstrated that preheating is a must to minimize those risks. The choice of material and prior microstructure are very important. Process development and industrial applications have demonstrated the superiority of induction hardening over conventional carburizing when limiting the investigation or process application to the treatment operation only. However, additional mechanical processes such as shot peening increases the fatigue properties of the material after treatment significantly and carburized gears have demonstrated excellent properties in this case.

**References**

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