Induction hardening of steering racks for electric power steering systems

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“Power-on-Demand”, maximum mileage, and more functionality – modern automotive steering systems need to offer all this, while being maintenance-free and low-weight at the same time. Most vehicles already use electric power steering to assist the steering movement, allowing for easy manoeuvring for parking or at low speeds. The core component of these complex steering systems is the steering rack, which is heavily loaded during use. Induction hardening increases steering rack wear resistance and service life. This article describes design features of electromechanical steering systems and the resulting demands on the steering racks. Various induction hardening methods and hardening machine types will be presented.

Power or servo steering (Latin: servus = servant) is used to reduce the human effort required for activating a vehicle’s steering wheel, primarily at lower speeds or when stationary. The driver’s steering effort is augmented by a hydraulic system or an electric motor. Although both system types have their advantages, electric power steering has become prevalent in recent times.

Electro-mechanical power steering features a speed-sensitive, electrical power-assisted steering system that is only active when needed to assist the driver. It operates entirely without hydraulic components. Compared to hydraulic power steering, it offers reduced fuel consumption and new comfort and safety functions: Active return of the steering to its centre point improves the steering feel around the mid-point, while cross-wind compensation comes to the driver’s aid when driving on a sloping road surface or in a constant crosswind [1].

With electro-mechanical power steering, a microprocessor-controlled electric servo motor on the steering mechanical system (steering column or steering gear) assists and boosts the driver’s steering movements. Hydraulic components, such as the servo pump and the hoses to and from the servo pump and steering gear, as well as the hydraulic fluid, are done away with. In the event of any mechanical damage, e.g., in an accident, there is no hydraulic fluid to escape, as only grease is used to lubricate electrically powered steering gears. Instead of hydraulics, an electric motor provides power to assist the driver’s steering movement.

A distinction should be made here between the various designs of electro-mechanical steering systems. The positioning of the servo unit (motor, control mechanism) and the design of the reduction gear determine the various types which are sub-divided as follows [2]:

- C-EPS = Column type Electric Power Steering; positioning of the servo unit in the steering column, gear type (worm wheel/shaft), e.g., in the BMW Z4.
- P-EPS = Pinion type Electric Power Steering; positioning of the servo unit on the steering gear pinion, as well as Dual-Pinion drive via a second, separate pinion shaft, gear type (worm wheel/shaft), e.g., in the Mercedes-Benz CLA class.
- R-EPS = Rack type Electric Power Steering; positioning of the servo unit in parallel or concentric around the rack, gear type (belt and ball screw assembly with a parallel-axis arrangement), e.g., in the VW Tiguan.

Depending on the vehicle type, electro-mechanical steering systems use over 90 % less power than hydraulic systems. For passenger cars that comply with the New European Driving Cycle (NEDC), this equates to fuel savings of up to 0.4 l/100 km (0.17 gal/100 miles) and up to 0.8 l/100 km (0.34 gal/100 miles) in city traffic, as the steering only uses power when the vehicle is actually being steered. There is no need to maintain constant hydraulic pressure [3].
With light commercial vehicles the fuel savings are even greater. Compared to hydraulic power-assist steering, an electric power steering system in compliance with the NEDC saves 0.6 l for every 100 km (0.26 gal/100 miles). At 25,000 km per year this produces a saving of 150 l (40 gal) of fuel thanks to the steering system alone. This amounts to around € 210 at a price of € 1.40 for a litre of diesel.

In terms of CO$_2$ emissions, too, there are considerable potential savings to be made. Compared to a hydraulic power steering system, electro-mechanical steering produces 16.1 g/km less CO$_2$. At 25,000 km per year this equates to a saving of around 0.4 t of CO$_2$. Furthermore, lawmakers have approved the introduction of an EU-wide CO$_2$ penalty for commercial vehicles that emit more than 147 g/km CO$_2$. With a limit of 175 g/km, it will come into force as early as 2014 and ensure that the limit of 147 g/km is reached in increments by 2020 [4].

**Table 1**: Advantages of electro-mechanical steering systems in passenger cars [3]

<table>
<thead>
<tr>
<th>Feature</th>
<th>Advantage</th>
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<tr>
<td>Safety</td>
<td>Stabilizing function</td>
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<td>Lane departure warning</td>
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<td>Collision-avoidance system</td>
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<td>Comfort</td>
<td>Steering correction system</td>
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<td>Park assist</td>
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<td></td>
<td>Lane keeping system</td>
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<td>Steering</td>
<td>Steering feel</td>
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<td>Steering performance</td>
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<td>Acoustics</td>
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<td>Emissions</td>
<td>Savings CO$_2$</td>
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<td></td>
<td>10 g/km*</td>
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<td>20 g/km**</td>
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<tr>
<td>Consumption</td>
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<td>0.4 l/100 km*</td>
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<td>0.8 l/100 km**</td>
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* NEDC (New European Driving Cycle) with a 2 liter Otto engine,
** city traffic only

In terms of CO$_2$ emissions, too, there are considerable potential savings to be made. Compared to a hydraulic power steering system, electro-mechanical steering produces 16.1 g/km less CO$_2$. At 25,000 km per year this equates to a saving of around 0.4 t of CO$_2$. Furthermore, lawmakers have approved the introduction of an EU-wide CO$_2$ penalty for commercial vehicles that emit more than 147 g/km CO$_2$. With a limit of 175 g/km, it will come into force as early as 2014 and ensure that the limit of 147 g/km is reached in increments by 2020 [4]. **Table 1** shows a summary of the benefits of electro-mechanical steering systems compared to their hydraulic counterparts.

Having highlighted the benefits of electro-mechanical steering systems, a closer look should be taken at the loads to which the steering racks are subjected. Fig. 1 shows the various applications of the three major designs of electro-mechanical steering systems, namely the C-EPS, P-EPS and R-EPS. Higher vehicle classes place higher loads on the rack. While for small to medium-sized cars, rack forces of 3 to 10 kN (675-2,250 lbs.-force) are to be expected, forces of between 9 and 13 kN (2,020-2,920 lbs.-force) for upper medium class cars and 13 to 16 kN (2,920-3,600 lbs.-force) for luxury cars, SUVs or light commercial vehicles should be anticipated. In cases where the load level is low, the servo unit is often fixed to the steering column (C-EPS), for mid-load levels it is secured to a second pinion (P-EPS), and where demands in terms of the rack force are high, it is fitted axially parallel to the rack (R-EPS).

As the load level increases, the force transmitted through the rack rises, resulting in the need for the rack to meet...
correspondingly greater wear resistance and service life requirements. Two induction-related aspects come into play here: the use of a base material that has been quenched and tempered and the induction hardening of the rack based on the mechanical processing method.

**INDUCTION HARDENING METHOD FOR STEERING RACKS**

This paper deals primarily with the second aspect, i.e., the induction surface hardening of the mechanically processed rack. An explanation of the upstream quench and temper process for heat-treating bars can be found in the literature [5].

**Induction hardening of steering racks**

Induction hardening is done to improve material properties. As a result of the structural transformation that occurs during hardening, the wear resistance, fatigue strength and – linked to this – the static strength can be improved [6].

With racks, too, induction hardening is limited here to the particularly heavily loaded areas of the workpiece (Fig. 2). These areas comprise the teeth and, depending on the type of rack, the shaft area, onto which a recirculating ball screw is incorporated after hardening. The areas to be hardened are subjected to an alternating electromagnetic field, which in turn induces an electrical current in the target area of the rack. The current flow heats the metal to approximately 900 °C (1,650 °F), after which it is quenched (i.e., rapidly cooled) directly using a special polymer emulsion and thereby hardened. The penetration depth of the induced current in the workpiece depends on the alternating current frequency and the material. For steering racks a hardening depth of just a few millimeters is usually required, which can be attained with an operating frequency within the 3-20 kHz range.

In terms of the induction hardening process, two different methods have been developed. These are known as "scan hardening" and "single shot hardening". With scan hardening, as shown in Fig. 3 (also called progressive hardening or progressive radial hardening), the heating and quenching take place at the same time, whereby a continuous relative movement between the fixed inductor spray head unit and the workpiece is required. With racks, the inductor spray head unit is usually guided along the stationary clamped rack. With single shot hardening on the other hand, heating and quenching take place successively in one or more stations. Single shot hardening is used for greater penetration depths and/or higher throughputs (Fig. 4).

There are pros and cons to both methods, which need to be weighed up depending on the hardening task and throughput requirements, insofar as both methods are even technically interchangeable in the first place. With single shot hardening, in general, the higher power requirements are offset by much shorter process times, whereas with progressive hardening lower throughput rates can be achieved with less power. There are even applications where both methods can be used at different points of the workpiece.
The induction hardening of steering racks is often performed in a protective atmosphere. Scale forms at temperatures within the austenitization range as a result of the oxygen in the environment. This scale would then have to be removed again from the racks at great cost and labour. Flooding the induction chamber with inert gas prevents scale formation, producing surfaces with virtually no scale residues.

With steering racks, the hardening process must be followed by a tempering process, to reduce the hardening-induced stresses within the rack. Tempering also reduces hardness somewhat, which is acceptable because the untempered surface hardness is usually higher than the final required hardness in the finished part. Tempering is done by reheating the rack to a temperature between 150 and 200 °C (300 and 390 °F). As an alternative to induction tempering, the rack can also be heated in an electrically heated tempering furnace. The tempering temperature and duration influence the hardness reduction, e.g., high temperatures and short durations may have the same tempering effect as low temperatures and longer holding times.

**HARDENING MACHINE TYPES**

The individual machining systems used for rack hardening are presented and explained in the sections below.

**Scan hardening of racks with vertical workpiece positioning**

Hardening machines with a feed axis are typically used for producing small batches. Machines with multiple vertical axes have been developed to increase productivity. The entire area to be hardened is ‘scanned’ progressively in the hardening station(s). Circumferential clamping of the workpieces, for example if the shaft and teeth need to be hardened, is not necessary.

The workpieces are clamped in position by means of a clamping device with a workpiece drive and a back stop. A rotation control device is fitted to the back stop, such that the rotation of the workpieces can be monitored to ensure a safe and reliable process. The back stop is designed such that the steering rack can deflect freely, i.e., without any significant back pressure during the heating process, in order to minimize distortion.

Since the tooth area is generally hardened without rotation, the rack needs to be clamped in the hardening machine with the correct orientation, or the machine has to be equipped with a manual alignment aid or, alternatively, a fully automatic aligning unit. As an alternative to this, the workpiece may be aligned in an external station and guided into the hardening machine by means of an automated system, e.g., a robot. External alignment has the advantage that it takes place parallel to the process without increasing the hardening process cycle time.

Rack hardening can be performed using round or form-adapted inductors, which can be designed with one or several turns. The design of the inductor is finally determined by the hardening task specifications and the required throughput. As a rule, multiple-turn inductors can be used to attain greater feed rates, as the area in which power is induced in the workpiece is longer than with a single-turn inductor.

Increasing the wear resistance and fatigue strength in the tooth area is essentially only required for the teeth. Hardening only the teeth and tooth base area, however, causes severe hardening distortion, increasing the time and labour involved in straightening the rack. In addition, there...
is an increased risk of cracks appearing in the hardening zone as a result of straightening. The back of the rack in the area of the teeth is therefore also hardened in order to reduce distortion. To attain a consistent hardening pattern in this area, the rack must be able to be positioned in the inductor. For this it must be traversed horizontally. Therefore each hardening station is equipped with an additional NC axis for horizontally adjusting the inductor. In this way, the hardening depth in the area of the teeth and in the back of the teeth can be adjusted precisely.

Hardening in the shaft area is done by rotating the workpieces. Roller burnishing for the ball screw assembly is applied in this area at a later point in time. For this the workpiece must be centred in the inductor. For shaft hardening it is not normally necessary to guide the inductors over the sensors, as the hardening distortion is minimal.

If the hardening machine is equipped with several hardening stations, the stations can be operated sequentially. The workpiece is changed on one station while hardening is performed on the other. The power supply to the stations is provided using a common converter (power supply), which is switched alternately between the stations. This then allows simultaneous hardening in parallel in the stations, whereby the process parameters can be individually adjusted for each station. Since the stations operate independently, productivity is correspondingly high.

To ensure the racks can be hardened with minimal scale formation, as described above, the inductor is installed in a casing that is closed off as close as possible to the workpiece. This casing is flooded with nitrogen gas to displace oxygen. Heating/hardening is therefore performed in an oxygen-reduced environment to minimize scale formation.

Interlinking of the vertical hardening machines is often done using a robot, facilitating sophisticated hardening cells, in which several manufacturing operations can be carried out (Fig. 5).

**Progressive hardening of racks with horizontal workpiece positioning**

The assemblies described above for a vertical hardening machine can, in principle, also be integrated into a horizontal hardening machine. A key difference with the horizontal machine design is that these machines feature an internal workpiece transport system and can be integrated into a production line. With this machine concept, too, various manufacturing steps can be implemented in one cell. For example, the workpieces can be hardened in one station, tempered in the next station and straightened in a further station. Transportation of the workpieces between the individual units is performed using a walking beam transport system. Loading and unloading of the walking beam is performed using a gantry crane.

One difference between the horizontal and the above-described vertical plant concept is the quenchant guidance system (Fig. 6). Whereas with the vertical hardening process the lower part of the rack is cooled throughout the entire process cycle and the cooling time decreases relatively as the feed rate increases, the exposure time of the coolant across the whole hardening zone remains constant with a horizontal inductor spray head arrangement. As a result, a more consistent microstructure can be formed. On the other hand there is a risk that defectively or incorrectly arranged spray heads could allow quenchant to enter the inductor, causing inconsistent heating and soft spots.

The hardening process may also be performed in a nitrogen atmosphere on these machines to minimize scale formation.

**Single-shot hardening of toothed racks with indexing table transportation**

In order to reduce production costs there are machine concepts available where the shaft area is hardened using the single-shot hardening method. Roller burnishing is applied in this area at a later point in time. To reduce handling times and ensure optimum capacity utilization, an indexing table for internal workpiece handing is used with this machine concept.

Loading and unloading takes place in one station, while the shaft is single-shot hardened in the next station. The tooth section is scan hardened in another station, as described above. There is also the option of setting up two additional stations for induction tempering on the indexing table (Fig. 7).

![Fig. 7: Indexing table hardening machine with two hardening stations; one for single-shot hardening and one for scan hardening (source: SMS Elotherm)](image)
Single-shot hardening is well-suited for hardening the shaft area, as the geometry here is cylindrical and the hardening distortion is correspondingly minimal. When clamping the steering rack, any imbalance that may occur when incorporating the teeth must be offset.

With this modular machine design, internal workpiece handing and clamping in the hardening stations is performed separately. For operators this has the advantage that only one workpiece needs to be examined and evaluated for quality approval purposes. With conventional indexing table concepts, one workpiece per clamping unit needs to be examined and evaluated on the indexing table, as the position of the workpiece is different in terms of the range of manufacturing tolerances in each clamping unit. The corresponding labour and costs associated with the approval are many times higher.

The single-shot hardening process can also be performed in a protective atmosphere. For this a split chamber is built around the inductor. The inductor is horizontally positioned with the chamber open. Then the chamber is closed and flooded with nitrogen during the hardening operation.

CONCLUSION
The current trend of downsizing automotive components also affects the steering rack. The technical improvements being made in electric power steering are essentially aimed at optimizing the efficiency and power density to extend its use to light commercial vehicles [7]. While the demands in terms of the service life and wear behaviour are constantly increasing, the components themselves cannot be any larger or heavier for weight reasons.

The induction hardening of particularly heavily loaded points of such racks, as well as the use of correspondingly high-quality, induction heat-treated starting material, represent solutions for overcoming this dilemma. The industry has developed sophisticated manufacturing solutions to achieve reproducible induction hardening results that meet relevant demands accordingly.

All the machine concepts presented in this paper use assemblies that have already been proven and standardized. These same assemblies can be flexibly reconfigured to create other custom solutions.

With modular induction machines of a horizontal or vertical design for the induction hardening of steering racks, manufacturers are well-equipped for current and future demands. From hand-loaded machines for smaller quantities through automated hardening machines in production lines to complex manufacturing cells, which integrate other processes as well as the actual induction itself, modern induction solutions offer perfect, tailor-made solutions for all requirements every time.

LITERATURE
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