Induction hardening versus case hardening – a comparison

by **Sascha Brill, Dirk M. Schibisch**

Reducing fleet consumption in the automotive industry or service-free operation of components in offshore wind mills during lifetime – all depends on the quality of the components used. Especially the heat treatment, here the surface hardening, plays an important role, on the one hand for keeping geometrical dimensions as small as possible, on the other hand for boosting the component's resistance to ever increasing loads. In times of growing international competition among the manufacturers of such components, an intelligent manufacturing technology is an essential asset. This article compares the traditional process of case hardening with induction hardening and proves that the induction technology mainly is advantageous, when it comes to the integration into manufacturing lines, high productivity, energy and resource saving production, flexibility of the material selection and reproducibility of the hardening results.

Cast, hot and cold formed steel parts frequently do not have the necessary microstructure properties to satisfy the demands in installed state. Different heat treatment methods can be used to increase or optimize the material properties, such as the wear resistance, strength or ductility.

Heat treatment is defined according to DIN EN 10052 as: "A series of operations in the course of which a solid ferrous product is totally or partially exposed to thermal cycles to bring about a change in its properties and/or structure. The chemical composition of the ferrous product may possibly be modified during these operations."

Heat treatment processes are generally divided into thermal (annealing and hardening processes) and thermochemical processes (diffusion and coating processes) (**Table 1**).

Table 1: Classification of heat treatment processes; according to [3]

Thermal processes		Thermochemical processes	
Annealing:	**Hardening:**	**Diffusion:**	**Coating:**
Normalizing	Quenching	Case hardening	TIN
Soft annealing	Bainitizing	Carburization	TIC
Stress-relief annealing	Induction hardening	Carbonitriding	TICN
Re-crystallization	Flame hardening	Nitrocarburizing	CrN
Coarse grain tempering	Laser beam hardening	Nitriding	etc.
Solution annealing	Electron beam hardening	Boriding	
etc.	etc.	Chrome plating	
		etc.	

While induction hardening belongs to the thermal processes, case hardening is a thermochemical process. Properly applied, both processes ensure a selective microstructure transformation of the surface layer so that measured from the surface down to a given depth, a complete martensitic hardened microstructure is generated. The core in the respective starting condition thereby undergoes no or only a limited transformation.

A precondition for the hardenability of the respective material is a corresponding carbon content in conjunction with a corresponding content of alloying elements. Furthermore, a careful examination of the right combination of workpiece geometry, hardening specification and heat treatment process is necessary. Table 1 shows common hardening processes. This article describes and compares the two processes, case hardening and induction hardening.

CASE HARDENING

Heat treatment processes such as case hardening are used to prolong the service life by increasing the surface hardness and vibration resistance while maintaining a ductile, elastic microstructure at the core. Case hardening steels to DIN EN 10084 or free-cutting steels to DIN EN 10087 can be used for case hardening. These steels have a carbon content of approx. 0.1 to 0.3 % w/w. Thanks to the low carbon content, these steels can be easily machined and formed. For a high surface hardness, for example 60 HRC, the carbon content of approx. 0.1 to 0.3 % w/w is not sufficient and the part therefore has to be carburized.

Carburization takes place by diffusion of the carbon into the workpiece surface. The C-level, i.e. the carbon level, is used to control the carburization process. During gas carburization, carburization takes place in two coordinated sub-processes: During the first step, the carburization depth is set using a higher C-level, while in the second step the C-level is reduced so that the percentage by weight of the surface carbon is obtained to the necessary depth. A gas mixture of carrier gas and additive gas forms the basis for the carburization atmosphere in the furnace. For example, propane and natural gas/methane is generated as carrier gas in a separate endothermic gas generator and heated to room temperature before admission to the furnace in order to prevent a further reaction of the gases. Direct gas admission to the furnace is a further possibility. Here, for example, natural gas with an addition of propane is admitted directly to the furnace atmosphere. Crucial factors for the right choice of the carburization process are the material-specific parameters, the hardening demands in conjunction with the gas composition and a continuous, homogeneous furnace atmosphere.

When assessing the hardenability of a material, a distinction is made between the carbon-dependent hardening capability (highest achievable surface hardness) and the alloy-dependent hardness penetrability (depth-hardening ability). The alloy components molybdenum, chrome and manganese are predominantly used for the latter process and influence the behaviour of the microstructure transformation. The transformation behaviour is dependent not only on the alloying elements involved, but is also influenced by the temperature and holding time, i.e. by the austenitizing conditions, and by the cooling rate, quenching medium and grain size.

Hardening is achieved by heating to austenitizing temperature with a sufficiently long holding time and subsequent quenching process. What is crucial here is that the carbon in the austenite is brought into solution. The amount of carbon is dependent on the material composition and the state of the initial microstructure. Excessive holding times or excessive temperatures during the austenitizing process can have a negative impact on the grain growth and material microstructure.

The hardening process can be followed by a low-temperature cooling process or direct tempering process. Both processes result i.a. in a reduction of the residual austenite and of the hardness and distortion properties. Low-temperature cooling is generally performed immediately after reaching room temperature. If this process is performed later, the austenite that has not yet been transformed may stabilize and can impair or prevent the reduction of the residual austenite. Furthermore, low-temperature cooling is employed where very high quality demands are made on dimensional and form precision in conjunction with temperature differences when using hardened parts.

Tempering is performed in different temperature ranges. The tempering temperature of parts made of low-alloy or unalloyed steels generally lies between approx. 180 and 250 °C. The higher the temperature is

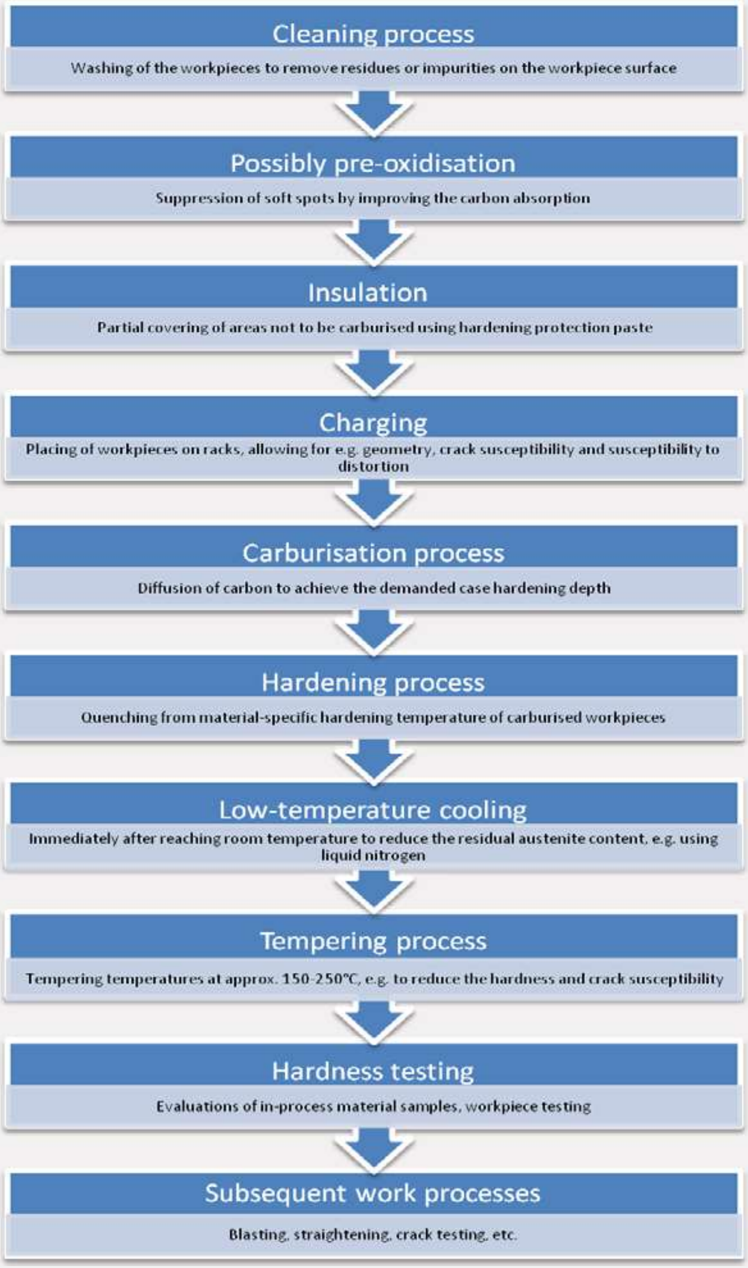

Fig. 1: Process chain of a case hardening process; according to [2]

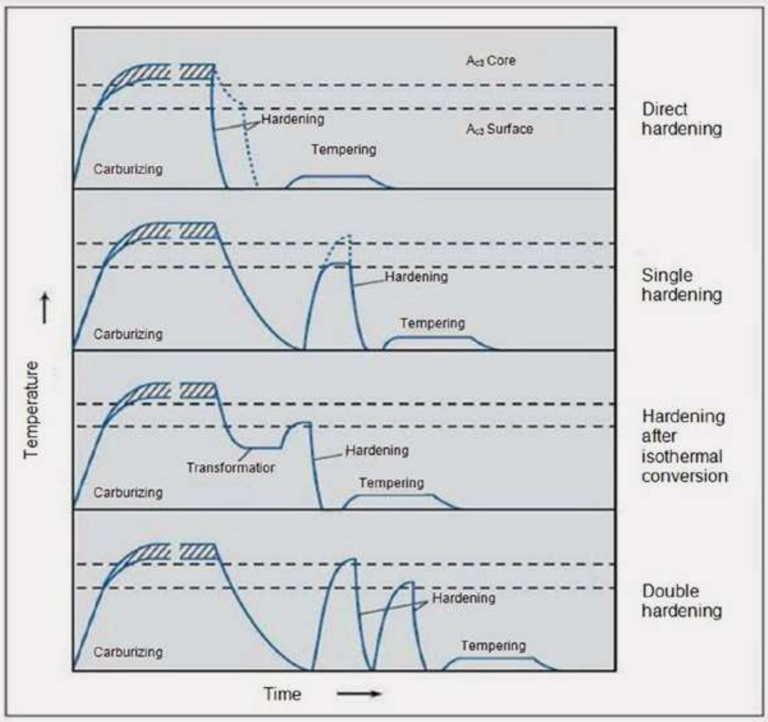

Fig. 2: Classification of possible case hardening processes; according to [4]

selected, the greater is the drop in hardness. High-alloy cold and hot working steels or high-speed steels, on the other hand, actually increase in hardness at temperatures > 500 °C. These are therefore also referred to as "secondary hardening steels". This increase in hardness results from the transformation of residual austenite into martensite in conjunction with a precipitation of carbides. For this reason a second tempering process is often additionally carried out when using high-alloy steels in order to temper the newly created martensite. This shows that the effects of the tempering process on the service properties of a part are attributable not only to the tempering temperature, but also to the alloying elements content. The overview in **Fig. 1** shows a typical process sequence for case hardening.

Upstream processes can have a crucial influence on the quality of the workpieces. These include, for example, stress-relief annealing under an inert gas at temperatures of approx. 580 to 680 °C to reduce the intrinsic stresses. The influence of inert gas serves here to minimize scaling. According to DIN 17022 Part 3, case hardening can be divided into further sub-groups (**Fig. 2**). These include the processes direct hardening, single hardening, hardening after isothermal conversion and double hardening.

Direct hardening

Direct hardening is performed immediately after the carburization process which, depending i.a. on the material and the hardening demands, takes place at approx. 900 °C. Immediately after carburization, the temperature is reduced to the material-specific hardening temperature. The carburization temperature can have a significant influence on the microstructure. At higher temperatures, the formation of coarse grains and a higher percentage of residual austenite in the surface area can occur. After reaching the required hardening temperature, the workpieces are quenched.

Single hardening

By contrast with the direct hardening process described above, single hardening consists of self-contained process steps. This means that carburization and hardening are two separate processes. Carburization means that the workpieces are cooled from the specific carburization temperature to room temperature. Carburized workpieces can then undergo intermediate machining. The workpieces can then be heated to hardening temperature again. The renewed heating to above the austenite transformation temperature causes a reformation of the microstructure. This is one of the reasons why the process can be used in particular after high carburization temperatures > 930 °C.

Hardening after isothermal conversion

As with direct hardening, this process involves reducing the temperature to approx. 600 to 650 °C after the carburization process. In this pearlitic transformation range, the temperature is held isothermally constant until the transformation of austenite to pearlite has taken place. After isothermal conversion, the workpieces are heated to the material-specific hardening temperature again. It is then quenched to room temperature.

Double hardening

As the name already suggests, this process involves hardening twice. After carburization, the workpiece is heated again to core hardening temperature and then quenched. This process is repeated, but the hardening temperature is reduced to the case hardening temperature. This process is used to homogenize the microstructure at the material core after the first process and to optimize the microstructure of the case layer after the second process.

In summary we can say that direct hardening and hardening after isothermal conversion are characterized by carburization and hardening in one step. Both processes generate a fine microstructure and also have the advantage that they require less energy compared with single or double hardening. Furthermore, less complex plant engineering is used than for double hardening. It should also be noted that direct hardening and hardening after isothermal conversion exhibit better properties with respect to changes in dimensions and form. All the methods include a tempering process as the final step in the respective hardening process.

INDUCTION HARDENING

By contrast with the conventional furnace technology, during induction heating the metal workpiece is subjected – partially or completely – to an electromagnetic alternating field using a current-carrying coil. This alternating field creates eddy currents in the material. These flow in the opposite direction to the original current and heat is generated (**Fig. 3**).

In the context of induction hardening, the expression short-cycle austenitization is also used, since by comparison with furnace processes the austenitizing temperature is reached within just a few seconds. The hardening temperatures are generally approx. 50 to 150 °C higher than with conventional furnace hardening. The process sequence during hardening consists essentially of heating, holding, quenching and possibly a subsequent tempering process, and is thus significantly shorter than the process sequence for conventional case hardening. The process is monitored by an appropriate control system so that the hardening results are reliably reproduced. The microstructure properties can be set to the required depth in carbon-based materials by varying the frequency employed, the energy input, the quenching method and the constant coupling distance between workpiece and inductor. The hardening process is tailored specifically to the hardening requirements (**Fig. 4**). Cylindrical workpiece geometries, for example, are hardened using the scan hardening or single shot hardening process. Depending on the modulus and geometry, gears can be hardened at the tooth flanks, at the tooth root or in the tooth gaps or completely as with single shot gear hardening using a ring inductor. On the workpiece in Fig. 4a, the middle rib was not hardened for strength reasons.

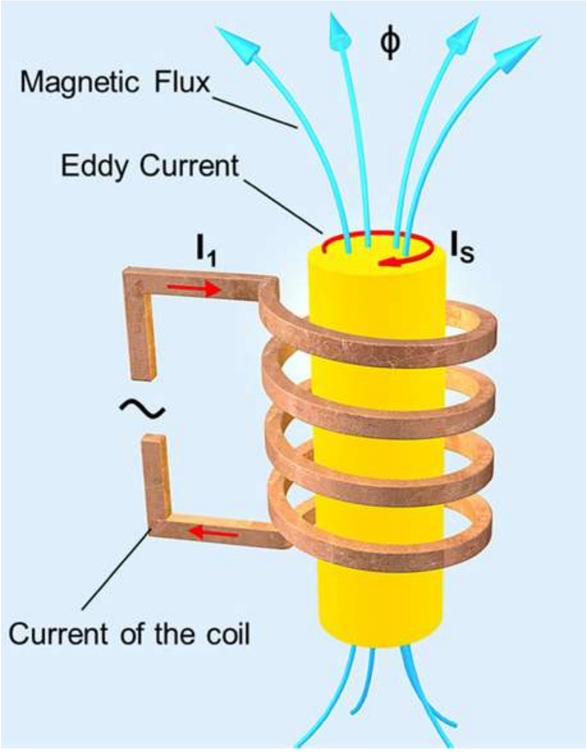

Fig. 3: Principle of induction

The work step of prior insulation or pre-oxidization that has to take place with furnace hardening can be completely eliminated with induction hardening. Furthermore, in view of the sensitivity to distortion, smaller grinding allowances can be used in many cases, further increasing the profitability of the process. The overview in **Fig. 5** shows a typical process sequence for induction hardening.

Fig. 4: a) Section through a double-race ball bearing ring with induction hardened raceways; b) simulation of induction hardening using an inductor (source: SMS Elotherm GmbH)

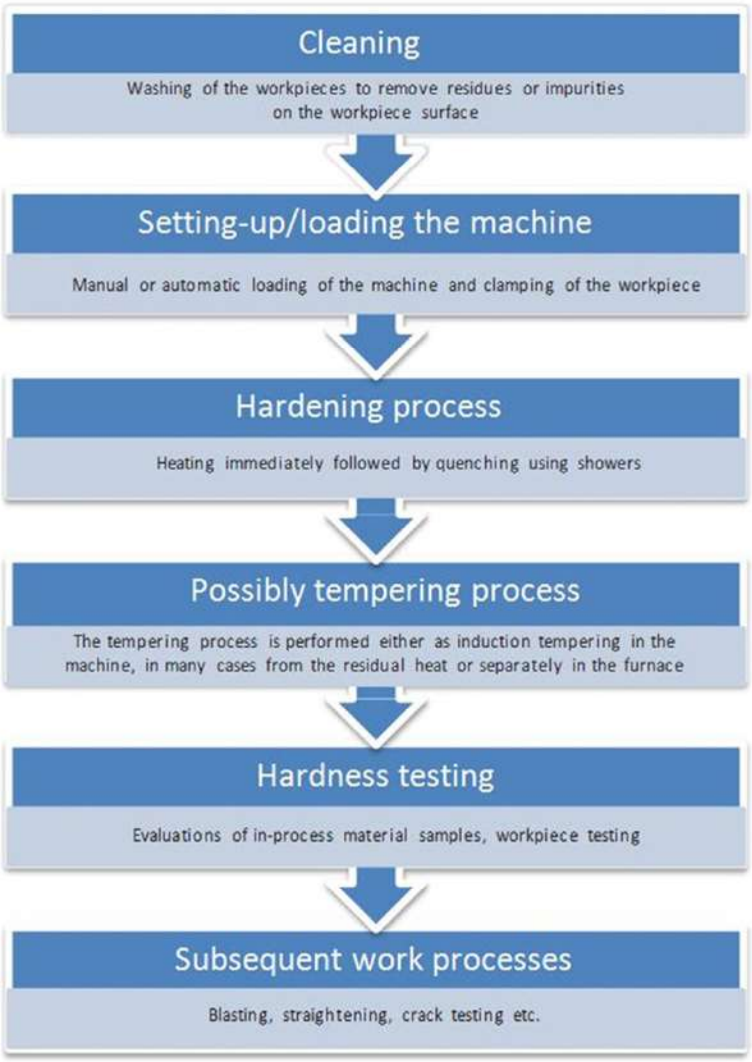

Fig. 5: Process chain of an induction hardening process

ADVANTAGES OF INDUCTION

The technical and economic benefits of induction are of enormous significance, particularly under the aspect of energy efficiency. Machine concepts tailored specifically to the customer's requirements offer on the one hand the possibility of integrating the induction heating unit into a production line, and on the other of having it operate as a separate, stand-alone system.

Modern induction hardening machines are characterized by great flexibility for a constantly changing and growing spectrum of parts. Relevant criteria are:

- Short cycle time,
- Direct integration into production lines,
- Reproducibility and process precision thanks to exactly designed inductors,
- Energy efficiency thanks to low heat losses, energy saving mode, continuously improved inverter technology and through partial heating and short heating time,
- Energy consumption only under load,
- Low re-machining costs,
- Low distortion,
- Low space requirements,
- Use of different quenching media,
- No dependence on fossil fuels,
- No additional exhaust gas emissions (small CO_2 footprint),
- Balanced price/performance ratio.

Modularized machine concepts are used for this in machine and plant engineering. Individual configurations are made possible on the basis of a wide range of different basic variants. As an option, these can be customized with numerous additional functions and hence tailored to the customer's specific application.

These include, for example, options such as:

- Number of workstations (single or double station, turntable),
- Manual or automatic loading,
- Single shot hardening or scan hardening,
- Individual combination possibilities for hardening and tempering process,
- Integration of intermediate work steps, e.g. post-cooling, fan cooling,
- Integration into manufacturing cells consisting of robot loader, straightening station, separate tempering station, re-machining station, etc.

Furthermore the hardening process can be designed such that induction hardening takes place in an inert gas atmosphere, for example by using a specially designed inductor. This is achieved by a corresponding inert gas flooding of the inductor chamber. This prevents scaling of the surface that can occur at temperatures in the austenitizing range due to the influence of ambient oxygen. Time-consuming re-machining steps are thus minimized or can be eliminated completely.

The induction hardening process is generally followed by a tempering step. This serves to relieve or reduce material stresses caused by the growth in volume of the material microstructure during the martensite formation. Furthermore, it allows the hardness after quenching of the workpiece to be brought to the lower hardness required by the customer's specification. This tempering process can be performed in different ways and should be adapted to the customer's individual requirements. The following tempering processes are available:

- Tempering from the residual heat,
- Induction tempering,
- Tempering in the furnace.

Tempering from the residual heat is frequently performed in the field of fully automated processes. A shortened

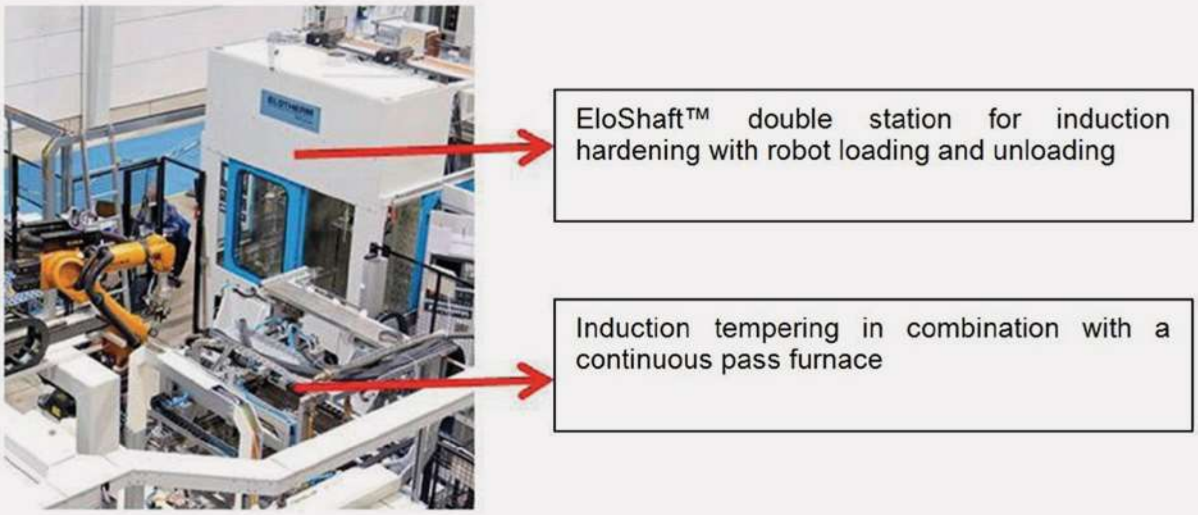

Fig. 6: EloShaft™: Integrated production cell (source: SMS Elotherm GmbH)

quenching time leaves enough residual heat in the inside of the part that thereafter a thermal equalization process is sufficient for the tempering of the surface. Only a slight reduction in hardness is achieved. The process of tempering from the residual heat can only be controlled to a limited extent due to the material and requires precise process control. This method is frequently preferred to cycle time and cost reasons.

Induction annealing is also used for fully automated processes. After a shortened quenching process, the workpiece is heated once again by induction for a short time before it is finally cooled. For cycle time reasons, the induction tempering process is frequently integrated into an additional workstation. Alternatively these processes can also be performed in the same clamping as the hardening process. By comparison with tempering from the residual heat, the more precise control of the heat input allows far more reproducible tempering results to be achieved and the reduction in hardness to be flexibly adjusted to within 10 HRC.

From the point of view of quality, tempering in the furnace is the most reliable method of ensuring a homogeneous reduction in hardness. Furthermore, material stresses in the workpiece before the induction hardening can also be minimized. Tempering in the furnace offers the possibility of ensuring a consistently high reduction in hardness in combination with a homogeneous temperature curve. Due to the time-intensive process (up to several days) and the considerable additional investment, tempering in the furnace is often ignored and one of the two other processes is employed.

In series production, the combination of an induction hardening process and downstream induction tempering section in a continuous-pass furnace can offer a higher degree of quality and cost effectiveness. This process can, for example, be integrated into a manufacturing cell (**Fig. 6**). The two processes are linked by means of a robot. The induction tempering process is performed horizontally in one shot. After a shaft has been deposited by the robot, it is indexed by a walking beam transport unit further into the continuous pass furnace.

A further example is the design of a double station. This allows induction hardening followed by induction tempering for a wide range of different workpiece geometries. The machine concepts proper, but also the necessary periphery for exact parameterization of the whole process, such as the inverter technology, the control unit or the mains transformer, the cooling of the electrical circuits, the cooling of the quenching medium, etc. are essential components for meeting the following demands:

- Fast reaction time for extremely short heating times,
- Continuous operation at nominal load,
- Variable frequency range,
- Integrated surge current and surge voltage protection,
- Standby mode: Switching off of all pumps and auxiliary units,
- Accessibility and ease of maintenance,
- Small installation space for the machine.

APPLICATION EXAMPLE: COST COMPARISON

The exemplary calculation refers to the pure energy consumption required for the defined heat treatment process described. Further costs, such as the acquisition of a shaft furnace or induction hardening system, charging and set-up, a charging rack, a quenching unit, further work steps such as e.g. insulation, straightening, blasting, and the personnel costs are not included due to the individual design.

Furthermore, the elimination or reduction of further work steps, such as pre-machining (grinding allowance), material procurement, hard machining or the blasting of workpieces offer a great cost reduction potential compared with a case hardening process. In view of the comparatively high wear of a shaft furnace and the necessary charging racks, additional costs are to be expected due to the increased maintenance.

Example 1: Case hardening of a case-hardened steel (16MnCr5)

Case hardening depth of approx. 2 mm and a hardness of 57-62 HRC in a shaft furnace:

Workpiece: Shaft diameter 30 x 500 mm, weight approx. 3 kg, charge size: 8 t

The total costs for an 8 t charge are € 1,353,-.

The process takes 46 hours.

Process step	Duration [h]
Heating	14
Diffusion	18
Hardening	10
Tempering	4
Total	46

Media	Costs [€]
Natural gas	1,149,-
Electricity	138,-
Nitrogen	10,-
Endothermic gas	36,-
Propane	20,-
Total	1,353,-

Example 2: Induction hardening of a quenched and tempered steel (42CrMo4)

Case hardening depth of approx. 2 mm and a hardness of 57-62 HRC by single shot hardening:

Workpiece: Shaft diameter 30 x 500 mm, weight approx. 3 kg (8 t thus corresponds to 2,667 shafts)

Cycle time/shaft: 20 s (consisting of heating, quenching and tempering)

Energy input required for hardening and tempering: 0.56 kWh/shaft

For an 8 t charge that means a required energy input of 1,492 kWh.

The total costs for an 8 t charge are thus € 150,-.

Pass time for 8 t: approx. 15 h

Media	Total costs [€]
Electricity	150,-

The comparison of the pure energy costs alone shows the superiority of the induction process by direct comparison with case hardening, if the workpiece is suitable for this method. In the example the process time for induction hardening of 15 hours for 8 t of workpieces (2,667 shafts) is only around one-third of the process time for case hardening of 46 hours. In other applications, such as the heat treatment of large roller bearings, the relationship is far more drastic: Whereas the induction hardening process for a ring of 3 m diameter takes around one hour, the heat treatment in the furnace can take almost one week. This does not even take into consideration the additional machining work to remove the resulting distortion.

The energy costs for induction hardening in the example of € 150 are lower by a factor of 9 than the energy costs for the furnace heat treatment of € 1,353. Possible additional savings from the elimination of the need to use CO_2 certificates are also not taken into consideration in this case, but do represent further potential.

CONCLUSION

Heat treatment processes such as induction hardening or case hardening are necessary to meet the enormous demands of industrial users on the quality and load-bearing capability of individual components. For example, the vibration resistance in the material can be optimized by both methods to such an extent that only in this way parts subject to high dynamic loads can be used at all.

The wide variety of different conventional hardening processes shows the various potential fields of application and should not be generally questioned. The creation of individual microstructures, particularly in steels with specific alloying elements, is made possible by carefully balanced heat treatment processes in the furnace. In many cases, however, an induction solution for achieving specific surface hardness parameters or microstructure properties is far faster and far more cost effective. The suppliers of induction heating technology are ready to share their know-how with the users.

Equally as important as the choice of the right hardening process is the choice of the appropriate plant engineering. The precise control of important process parameters in induction hardening systems makes a vital contribution to fulfilling quality and cost efficiency demands. The energy cost calculation alone shows a significant difference in the comparison of the two processes in favour of induction hardening. The high investment costs for heat treatment furnaces are in stark contrast to the comparatively low costs for the corresponding induction heating facilities. The customized integration of induction heating into complex manufacturing processes ensures cost-effective production. The ecological aspect of using electrical energy instead of fossil fuels in order to avoid emissions of CO_2, NO_X or SO_X is mentioned only in passing at this point.

For these reasons, induction heating technology has already established itself firmly in many branches of industry, such as in the automotive sector or in wind power. A prolonged service life for complex parts is the most important criterion that will continue in the future to be a basic prerequisite for innovative component developments in the area of the powertrain for cars and trucks or for parts of offshore wind turbines subject to high loads.

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