Electromagnetic-thermal coupled simulation of induction hardening for excavator chains

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Complex workpieces and extensive prototypes require a special detailed engineering. This paper gives a brief overview about several process techniques which can be used in induction hardening and describes in detail an electromagnetic-thermal coupled simulation. The computational mechanical engineering with ANSYS 17.0 was done for a complex inductor geometry which was used to harden big excavator chains. The simulated inductor was built and installed in one of the flexible hardening machines of Härterei Reese Bochum GmbH where a chain was hardened and evaluated. These results were used to validate the simulation.

The main advantage of induction hardening is the direct generation of heat within the part and directly below the surface. In general, all electrically conducting materials can be heated by induction but technically only steel, cast steel and cast iron above a carbon content of 0.2 % show enough hardenability.

Induction hardening helps to improve the wear resistance on the surface or the strength in the near-surface area whereas the ductility of the part's core is kept to help the part withstand dynamical loads.

The hardening process starts with a short-term austenitization where high power density is applied for a relatively short time to the workpiece. Changing the temperature to above 900 °C allows for the change from body-centered cubic lattice structure into a cubic face centric structure, called Austenite. A subsequent quenching process freezes the distorted lattice structure, which causes a change in volume of the workpiece and braces the lattice which macroscopically corresponds to an increase in hardness.

We can determine the hardness depth and hardness for different quenching speeds using a material-specific CCT diagramme. The high level of hardness after quenching is mostly unfavourable as it may cause cracks and limits life time in dynamic load cases so that typically a tempering operation is applied either by induction, from residual heat or in a furnace.

Using induction hardening means high reproducibility and fast process times. This ensures high product quality in short cycle times and enables the economic integration in various production lines.

WHICH MAIN COMPONENTS ARE NEEDED FOR THE HARDENING PROCESS?

The selection of system components is an essential part of the considerations for the hardening operation of the major part of the chain. The chain link requires a detailed examination of the hardening task especially including the workpiece's special geometry, the specification of hardness and hardening depths, and the material properties. The following checks will be carried out for the evaluation of system components:

- Material properties (carbon/alloy content, hardness after quenching, hardenability, etc.)
- Workpiece geometry (dimensions, hardness zone, gears, edges, undercuts, etc.)
- Matching the available and required depth of hardness
- Matching the available and required surface hardness
- Review of limit hardness
- Required soft zones
- Grain size.

For induction hardening typically high power densities at medium frequency level are needed. The selection of the converter power and frequency is mainly based on the intended hardening depth and grain size to allow for a sufficiently high heat flux to the workpiece. The efficiency of the system components (converter, capacitor, busbars, transformer) and most of all the heating coil, the so-called inductor, reduces the available power, so that about 50–70 % is transferred into the workpiece. The energy transmission is contact-free. This is based on the ability of the inductor to build up a magnetic field over the distance to the workpiece, the so-called air gap. A high reactive power is required to generate the required electromagnetic field. This should not be taken from the customer's power grid so that capacitors are used. The output transformer acts as an electrical gear. Switching of both the capacitors and the transformer allows to maximize the converter's output power at the favoured frequency within a large frequency range. As a result, different workpieces at different dimensions and different frequencies can be hardened. With the patented solution from SMS Elotherm the workpiece heating power is measured and each produced part is monitored. Incorrect inductor position, false inductors or other process errors can be detected.

CHOOSING THE RIGHT INDUCTION HARDENING METHOD

During induction hardening, there are two basic process approaches, which bring both advantages and disadvantages. The scanning method is defined by a movement of the inductor relative to the workpiece during the heating phase. Typically, the entire area of the defined hardening zone will be covered throughout the scan. A shower attached upstream of the scanning direction ensures a sufficiently fast quenching. General-purpose inductors, which can be used for example for the same shaft diameter but different lengths are the main advantage of the scanning process. Thus, it saves tooling costs and reduces the change over time during workpiece set-up. On the other hand, higher cycle times will be achieved by this approach increasing linearly by the part dimension. This disadvantage may be compensated by using more hardening stations and tools.

An alternative approach to ensure a short cycle time without the need of multiple hardening stations and tools is the single-shot operation. Here, the inductor is fixed and the entire hardness zone will be heated in-place. Often a possible additional relative motion of the workpiece, e. g. an oscillating movement or, for cylindrical parts, a rotational movement, is required.

As mentioned, a rotational movement cannot take place if non-cylindrical surfaces are to be hardened. In such applications, the rotation is replaced by an oscillating movement. Thus, the heating conductor does not map onto the workpiece but blurs the temperature fields in the direction of the oscillation. Seeing e) from **Fig. 1**, the oscillation path should be chosen such that a homogeneous heating of the entire surface can be realized. Considering a meander-shaped inductor, as indicated in **Fig. 2**, there is a defined distance between the individual copper profiles in the transverse direction. The electromagnetic field propagates directly under the copper profile, so that temperature maxima are formed there and temperature minima are formed in the intermediate spaces. In order to achieve a uniform temperature level, the half pitch of two neighbouring copper profiles is used as an oscillation path. The complete hardening procedure is defined by several oscillations of the inductor during heating followed by the retraction of the inductor and immediate quenching with the fixed shower.

The main advantage of the single-shot approach (**Fig. 3**) is the short cycle time using one single inductor that may be adapted even to complex hardening specifications. On the other hand, the inductors are manufactured in a customized manner and can seldom cover several hardening zones.

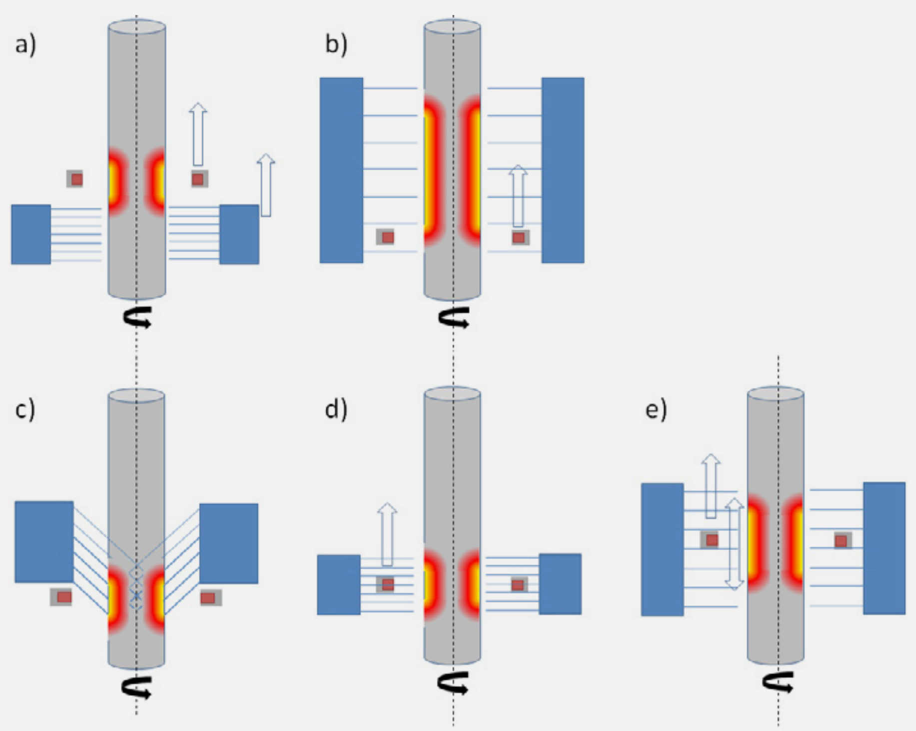

Fig. 1: Several versions of hardening applications – a) and b) for scanning, c)-e) for single-shot

ELECTROMAGNETIC-THERMAL 3D-SIMULATION

Inductor development is mostly a complicated process including design, manufacturing, testing and evaluation. This prototyping is based on experience, mostly including databases of previously build inductors. Experimental investigations have to be run to adapt hardening specifications. Hereby, small inductor modifications like changing coil width, amount of electrical sheets, coupling gap, etc. can be performed to achieve the desired hardening profile. With the help of this empirical method the right inductor coil geometry and the hardening result are achieved. Of course, all selected experience during these trials will be documented in the database for future work.

If the inductor is an expensive and complex prototype or if the price of the workpiece is quite high experimental investigations will not be economical anymore. Therefore, electromagnetic-thermal simulations will be applied. Their complexities are strongly depending on the workpiece geometry and could be reduced from 3D- to 2D- or even to 1D-problems. The equations are partial differential equations of first order which have to be solved with the help of boundary conditions and a finite element method.

Hardening Task

The task deals with hardening chain links which are used in hydraulic excavators. In the field the workpieces are subjected to high loads and abrasive wear. With the help of inductive hardening a uniformly high surface hardness depth has to be achieved – in accordance with very specific customer requirements. For this purpose, the two zones shown in red are hardened with a specific inductor (Fig. 2). After the heat treatment, the absence of cracks on the surface must be detected by a magnetic powder cracking test.

Set-up of the calculation model

The geometry of a chain link is too complex to reduce it to a 2-D or even 1-D problem. Thus, only the mirror symmetry of the component is used for a model reduction. The required surface hardness depth is much greater than the penetration depth of the induced current, which flows near the surface due to the skin effect. In the case of a meander-shaped inductor temperature maxima and minima (see Fig. 2) occur during a stationary hardening, which are compensated by an oscillating movement. With the interplay between induced heat and heat conduction, a large hardness depth can be achieved without generating surface overheating. The temperature-dependent material properties such as thermal conductivity, permeability, specific heat capacity, to name only a few, require a transient calculation of the coupled system.

The electromagnetic field, which is built up by the heating conductor with alternating current, transfers to the

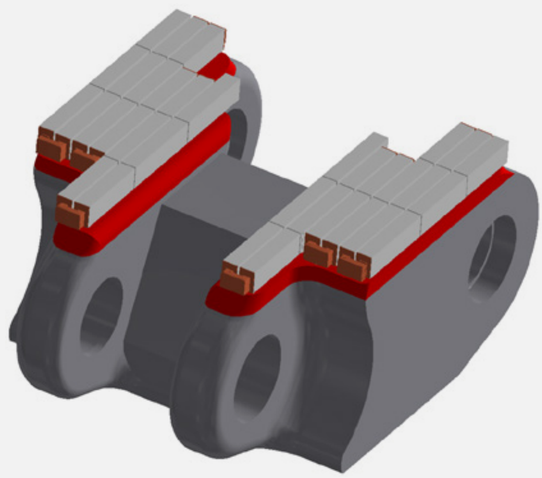

Fig. 2: Chain link hardening with a single-shot hardening inductor – hardening zone in red

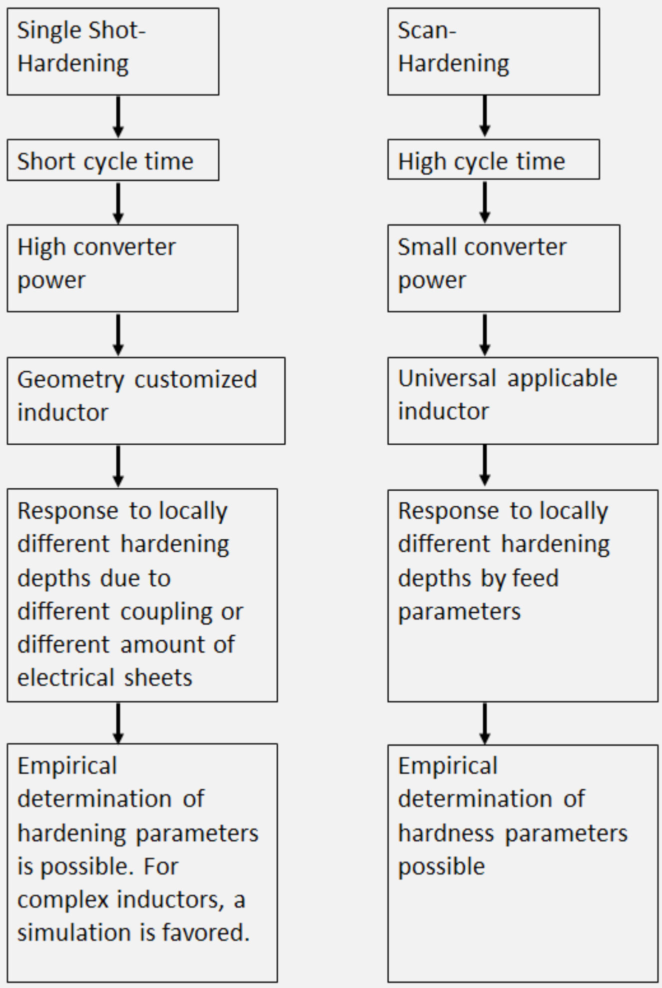

Fig. 3: Single-shot hardening vs. scan hardening

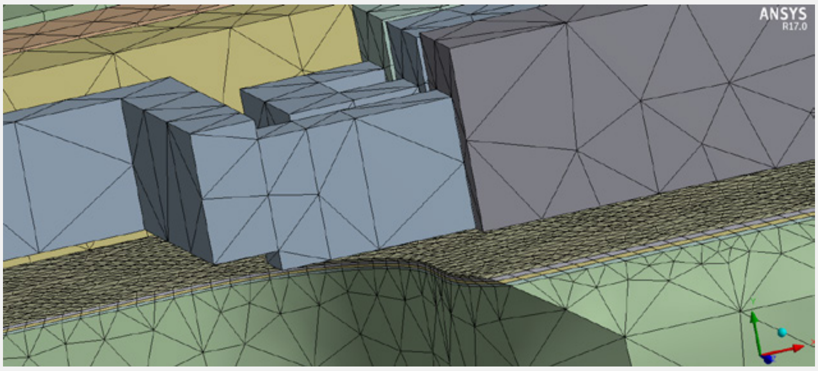

Fig. 4: Calculation mesh – Refinement of the skin effect region

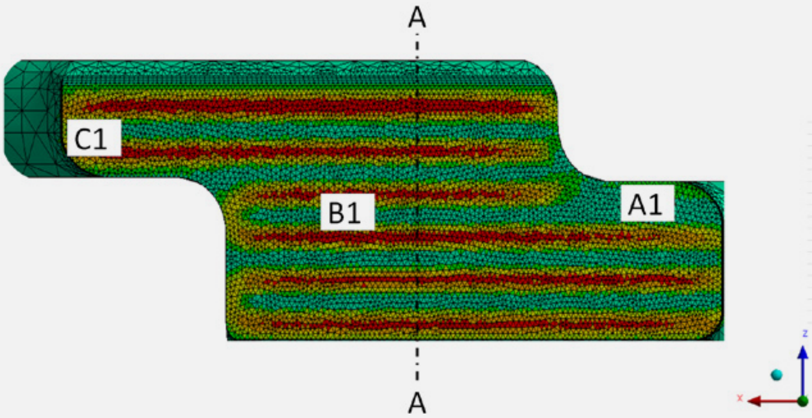

Fig. 5: Joule heat – image of the heat conductor on the workpiece

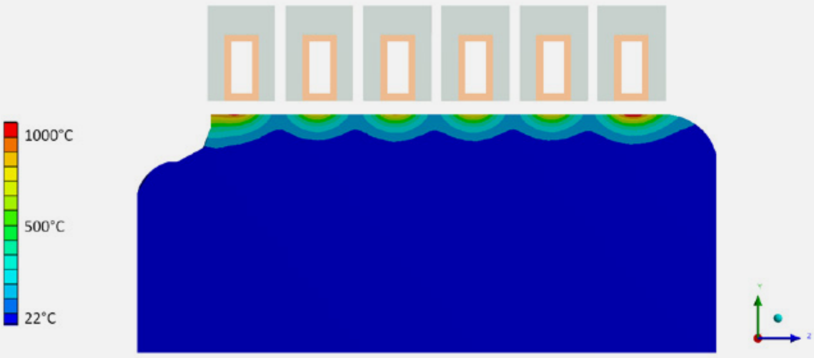

Fig. 6: Direct heat transfer of the induced current in section A-A in one second

workpiece and induces an alternating current. Due to the skin effect, this alternating current flows on the workpiece surface and can be changed by a frequency adjustment in the depth direction. For this reason, high penetration depths require lower frequencies. The electromagnetic computation results in the Joule heat which is generated in the workpiece. Due to the temperature changes and the accompanying changes in the material properties a feedback is made to the electromagnetic calculation. The calculation mesh of the inductor can be set relatively coarsely. By reason of the skin effect (**Fig. 4**) the surface region of the workpiece must be meshed in fine layers so that the power density drop can be determined adequately in regard to the penetration depth. From experience, a precise calculation requires five layers to determine the resulting power density drop numerically. The penetration depth can be described by the following equation:

$$\delta = \sqrt{\frac{1}{\pi \cdot \mu_0 \cdot \mu_r \cdot f \cdot \sigma}}$$

with δ = penetration depth, μ_0 = magnetic constant, μ_r = relative permeability, f = frequency, σ = electrical conductivity

Simulation and process adjustment

During the simulation various copper profiles and inductor designs were tested in order to achieve a homogeneous heating. The achieved uniform temperature distribution prevents local overheating which can lead to coarse grain size formation or even surface melting.

Fig. 5 shows the Joule heat, which has its maxima directly below the heat conductor profile. The distance between these maxima corresponds somewhat more than the selected profile width and defines the oscillation path. But which oscillation speed is necessary? For this purpose, the thermal-transient calculation is used in which the inductor is positioned fixed above the workpiece and generates the heat for a defined heating time.

Fig. 6 shows the temperature distribution along the intersection plane A-A, which was reached after only one second. The surface temperature under the heating conductor profile is an average of 900 °C and decreases along the depth of 11 mm. Since the chain link acts as a sink and the temperature flows into the interior of the workpiece, the surface can be reheated after an oscillating cycle. After a certain period, the temperature saturates at the surface since the temperature difference becomes smaller.

The consequence of saturation is reflected in a heat accumulation and the corresponding temperature increase which can be tolerated up to a limit of 1,050 °C without excessive grain growth. The professional cooperation with the hardening shop Reese Bochum GmbH enabled the precise mounting of thermocouples which were positioned in

4 mm, 16 mm and 25 mm depth distributed over the workpiece. Thus, the number of test parts could be limited to a minimum and unnecessary laboratory evaluations could be avoided. **Fig. 7** describes three pairs of temperature curves in several depths which are identically positioned on both hardening zones. The slight differences between two temperature curves at one defined depth are caused by the manual drilled holes of each individual thermocouple. With the help of these measurements, the limit temperature of 1,050 °C could be detected and reduced at specific intervals with targeted power reductions. The uniform temperature development on both sides highlights the good workpiece positioning and inductor production.

A large surface hardness depth can be achieved during induction hardening in conjunction with the heat conduction and requires a heating phase of 12 minutes for this application. A subsequent extensive quenching process ensures microstructural transformation and prevents the tempering due to residual heat.

The hardness result was adequately met by the exact inductor design and process setting. The hardening distributions were carried out at the measuring points A1, A2, B1, B2, C1 and C2, as shown schematically in **Fig. 8** – the letters A–C representing the measuring positions and the values 1 & 2 represent the hardened surface of the chain link. The hardening depths of the pairs A1-A2, B1-B2 and C1-C2 differ only slightly due to workpiece tolerances and underline the homogeneous operation of the inductor on both surfaces. The minimum hardness depth has been clearly and reliably exceeded for all measuring points and emphasizes the good simulation and process design. The absence of cracks on the surface was also detected by the magnetic powder cracking test.

SUMMARY

In recent years, the demands on chain links have increased steadily. This applies both to the selection of the material and to the type of hardening. When in the past the process of flame hardening was often chosen, the desire to meet the hardness requirements by induction hardening increases with increasing demands on high reproducibility and absence of cracks. The hardening shop Reese Bochum GmbH has been known for many years to develop especially complex hard-

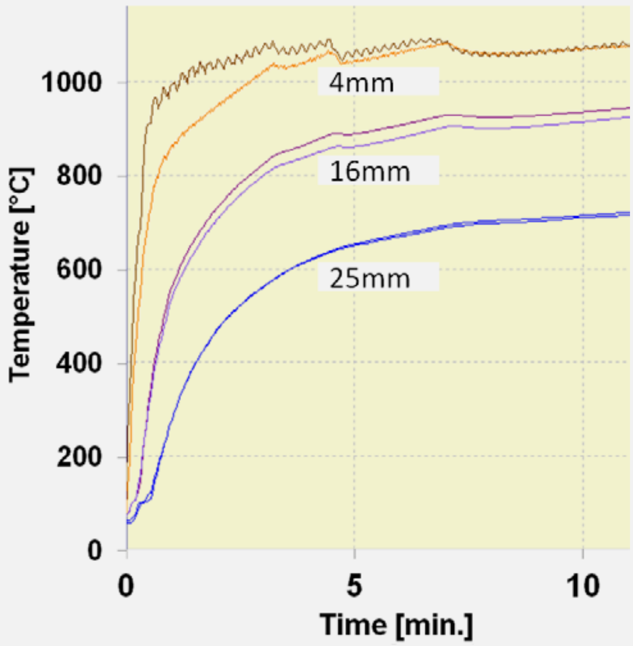

Fig. 7: Temperature curve during heating up at different depths

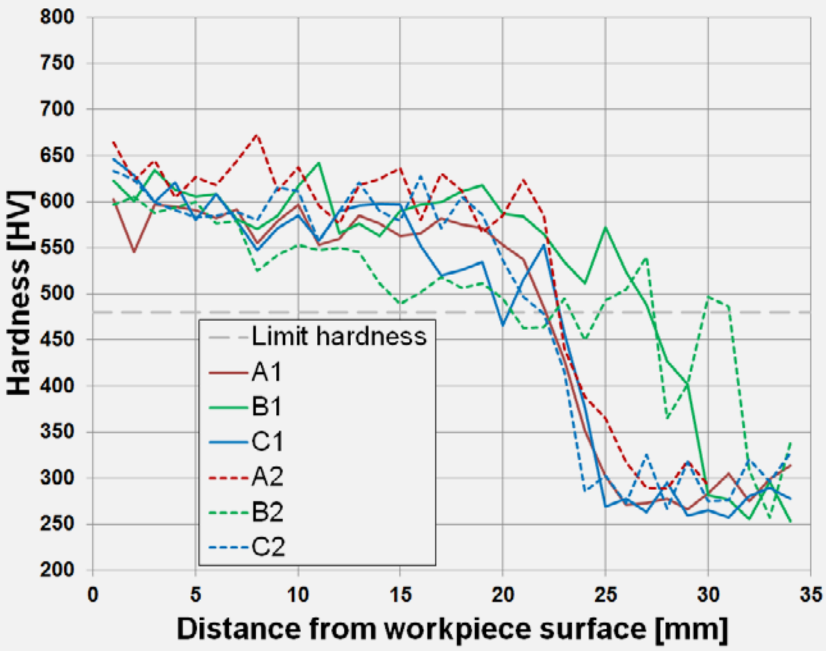

Fig. 8: Hardening distributions at three equally positioned measuring points on both chain link surfaces

ness problems and – in cooperation with competent partners – to develop market-oriented solutions. The good cooperation of the SMS Elotherm engineers with the heat treatment specialists of the company Reese led to the development of a new machine which meets all customer requirements. With this new machine Reese can now also offer the hardening of chain links via inductive heating and has thereby created another significant area in the large field of the mining industry. This success is mainly due to the partnership between SMS Elotherm and Härterei Reese Bochum GmbH.

LITERATURE

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