International Scientific Colloquium
Modelling for Electromagnetic Processing
Hannover, October 27-29, 2008

Investigation of relative magnetic permeability as input data for numerical simulation of induction surface hardening

T. Zedler, A. Nikanorov, B. Nacke

Abstract

This paper is devoted to the investigation of relative magnetic permeability as input data for numerical simulation of induction heating for surface hardening. The relative magnetic permeability of ferromagnetic steel heavily depends not only on such parameters as magnetic field intensity and the process temperature, but also on the actual chemical composition of steel. Information contained within present reference books is restricted to data about plain carbon steel e.g. C45. These properties can significantly differ from the properties of steel actually being used and therefore cannot always be recommended for implementing to a numerical model. A method of relative magnetic permeability determination has been developed and applied in order to increase accuracy and reliability of material data. At the same time, because of some special features of induction heating for surface hardening, the sensitivity analysis has been carried out to estimate the accuracy required in determining the properties in order to implement them to numerical models.

Introduction

Induction surface hardening is an extremely effective heat treatment process used to improve the quality of mechanical components. Main advantages of the induction heating process are contactless energy transfer, possibility to heat the workpiece partially, very short heating time, high power densities and controlled temperature distribution within the workpiece. During the heating phase, the workpiece is heated with a high frequency up to the austenitized temperature, followed by quenching. This results in a hard martensite structure present in the surface layer of the workpiece only.

Mathematical modelling is one of the major ways for successful design and optimization of induction surface hardening systems. However, numerical analysis of such processes is very complex transient heating with coupled electromagnetic and thermal fields. The calculation of the numerical analysis has to take non-linear material properties into account. Knowledge of the material properties represents an actual problem in the computation of the induction heating process because the outcome of the simulation is directly dependent on the accuracy of the input material properties. The major difficulty for modelling an induction heating process is to define the relative magnetic permeability of steel.

The investigation concerning the material properties and especially the relative magnetic permeability can be subdivided into two main directions: to increase the accuracy and reliability of the material data and to carry out sensitivity analysis to estimate the required accuracy in determining the properties in order to implement them to numerical models.

1. Relative magnetic permeability of ferromagnetic steel

Most electro- and thermo-physical properties of ferromagnetic steel like electrical conductivity, specific heat and thermal conductivity are functions of temperature. In contrary to them, the relative magnetic permeability μ_r depends on two parameters simultaneously: magnetic field intensity H and temperature T. This dependency for plain carbon steel (C-content of 0,22-0,99 percentage in weight) is shown in Fig. 1.

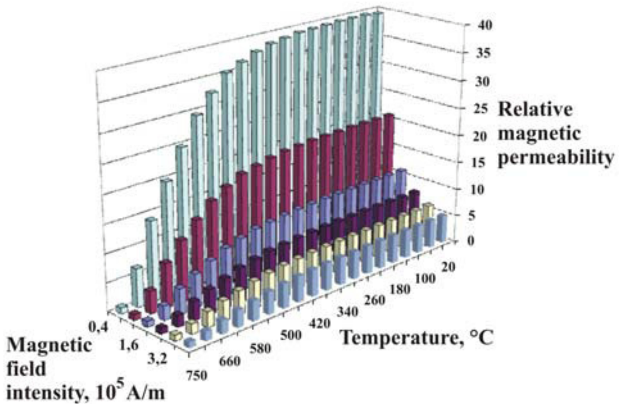

Fig. 1: Relative magnetic permeability μ_r as a function of magnetic field intensity H and temperature T

In a strong magnetic field ($H >> H_k$), which is typical for induction heating, the relative magnetic permeability decreases with increasing H (see Fig. 2a). Because of energy absorption in conductive material, the magnetic field intensity drops down exponentially toward the core of the workpiece (see Fig. 2b). Below the critical temperature T_c known as the Curie point (for

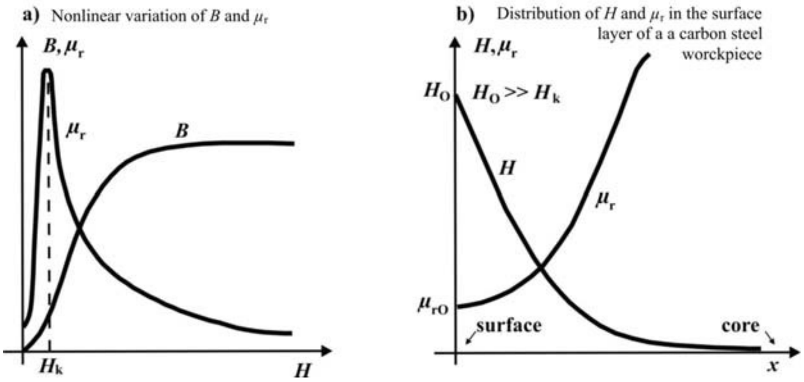

Fig. 2: Distribution of magnetic field intensity H and relative magnetic permeability μ_r

ferromagnetic steel $T_c = 740 \div 780°C$), μ_r goes down slightly as shown in Fig. 3. Above the critical temperature T_c, the relative magnetic permeability drastically drops to a unified level because the steel becomes paramagnetic.

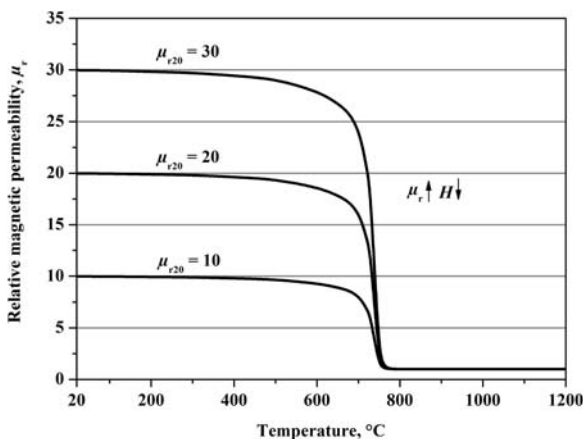

Fig. 3. Distribution of relative magnetic permeability μ_r dependent on temperature

Steels, used for induction surface hardening, vary in their chemical composition and therefore their properties can differ from the properties of plain carbon steel. In order to maintain reliable simulation results, $\mu_r(H,T)$ should be determined individually for each sort of steel. A typical approach to input the relative magnetic permeability is to use a temperature dependent curve, shown in Fig. 3, with a start value of μ_r at 20°C taken from the curve shown in Fig. 9.

2. A method of relative magnetic permeability determination

2.1. Basic concept

Direct measurement of μ_r under real induction heating conditions is very difficult because of high temperature and strong magnetic field. An alternative way to determine the relative magnetic permeability is based on the method used to solve inverse problems. It entails identifying μ_r by indirect parameters taken from experiments and numerical simulations. For successful solution of the identification problem, the examined induction system has to respond with maximal sensitivity to the unknown value. In the case of μ_r the flat induction system reaches highest sensitivity if the workpiece thickness d is approximately one third of the electromagnetical penetration depth δ (Fig. 4). This ratio can be provided by corresponding operating frequency.

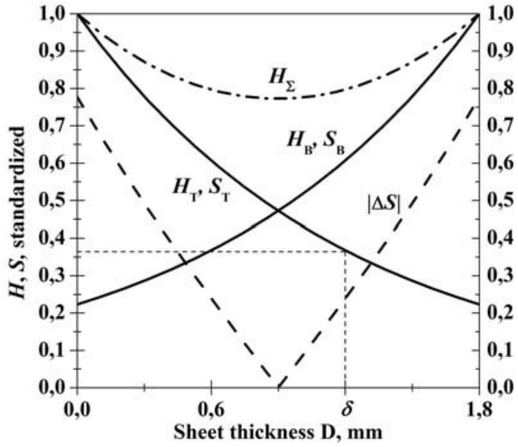

Fig. 4: Magnetic field intensity H and current density distribution S in the steel sheet

If a steel sheet of thickness d is heated in a longitudinal magnetic field under condition $d/\delta < 3$ it results in a snap-shot of current density distribution ΔS shown in Fig. 4. The heating behaviour of the steel sheet depends on the induced power which is proportional to the square of current density. Therefore, the temperature of the steel sheet has been chosen as the indirect parameter for determination of μ_r. Numerical computations with the adapted dependency $\mu_r(H)$ are repeated until the warm-up behaviour of steel is as close as possible to the experimental one. The newly found dependency $\mu_r(H)$ is excepted as the most reliable for this particular sort of steel.

2.2. Test arrangement and measurement approach

The test arrangement for indirect measurement of $\mu_r(H)$ has been designed and built at the Institute of Electrotechnology, University of Hannover. The block diagram of the set-up is shown in Fig. 5. The power supply (1) consists of the three-phase transformer, the MF-frequency converter, the compensation capacitors and the matching transformer. The load circuit includes the longitudinal field inductor (2) with test steel sheet (3) inside it. The temperature is measured by thermo-couples (5) fixed on the surface of the steel sheet. Measurement system DELPHIN (6) is connected via ETHERNET-cable (7) to PC (8) where the measured values are processed.

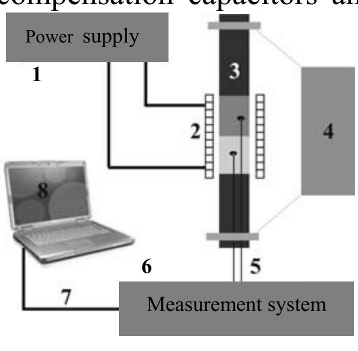

Fig. 5: Block diagram

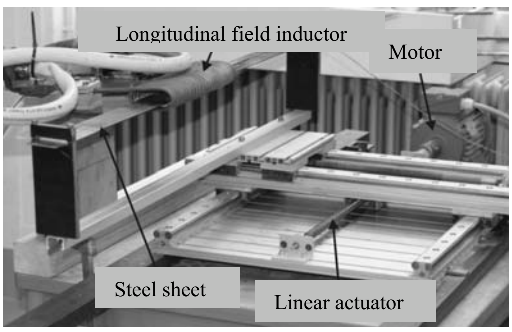

Fig. 6: Test arrangement

Fig. 6 shows the arrangement of the induction coil, the test steel sheet, positioning platform with the motor and the linear actuator. The test steel sheet used for experiments had the thickness $d = 1{,}8$ mm. Chemical composition of the experiment steel in comparison with the plain steel C45 is shown in Fig. 7. One can see a significant difference in chemical composition, particularly with regard to the C-component. It is known from reference literature [3] that the C-content has a strong influence on the actual location of the $\mu_r(H)$-curve.

With the designed test arrangement it is possible to warm-up the test steel sheets of up to 50 mm in width within a few seconds to 700°C. Two frequencies of 2050 kHz and 3100 kHz have been applied for investigating the warm-up behaviour of the experimental steel (see Figs. 10 and 11) taking into account the condition $d/\delta < 3$, mentioned above for identification of $\mu_r(H)$, when the test steel sheet thickness is of 1,8 mm.

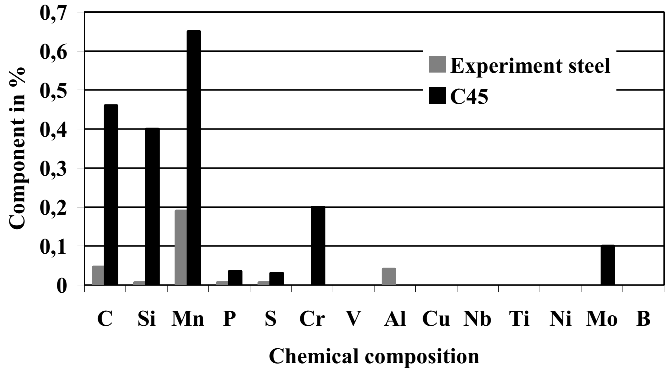

Fig. 7. Chemical composition of experiment steel and steel C45

2.3. Simulation model

One-dimensional process analysis has been realized by two-dimensional geometry of computation area shown in Fig. 8. The following main assumptions are valid in the model used:

- the steel sheet is to be seen as being placed inside the uniform longitudinal magnetic field,
- temperature dependent material properties of steel are taken into account,
- $\mu_r(H, T)$ is implemented as a temperature dependent curve (Fig. 3) with a start value of μ_r at 20 °C taken from the curve shown in Fig. 9,
- required magnetic field intensity is provided by the induction coil current, which is applied to the model as an input parameter.

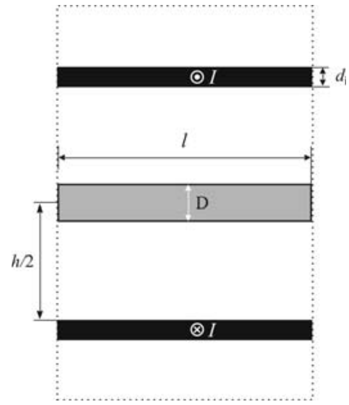

Fig. 8: Simulation model

The heating modelling process is organized in an iterative loop, where the Joule heat from electromagnetic calculation is used for thermal analysis and the received temperature distribution is taken to correct the temperature dependent electro-physical properties for electro-magnetic calculation at the next time-step. The result of the simulation is the temperature distribution at the final time *t* as well as the temperature time-history in the steel sheet.

2.4. Results

For determination of $\mu_r(H)$-dependence, the warm-up behaviour of the test steel at 3100 kHz has been selected.

At first, simulations with the $\mu_r(H)$-curve, typical for carbon steel (Fig. 9), have been done. The best-reached numerical result is shown in Fig. 10. As one can see, there is a significant difference between the experimental and the numerical results especially in the area of maximum temperature. The most probable reason for this difference is that the value of μ_r is too small. It is expected that the actual location of the $\mu_r(H)$-curve should be above the typical one.

At the second step, new best-reached values of H_{new} and μ_{rnew} has been found independently on the typical $\mu_r(H)$-curve. By means of the received correction coefficients

$$H_{cor} = H_{new}/H_{old} = I_{new}/I_{old} = 0{,}87, \quad (2.1)$$

$$\mu_{r\,cor} = \mu_{r\,new}/\mu_{r\,old} = 1{,}5 \quad (2.2)$$

the new $\mu_r(H)$-curve adapted for the test steel has been constructed (see Fig. 9). This curve is located slightly above the typical one as was expected.

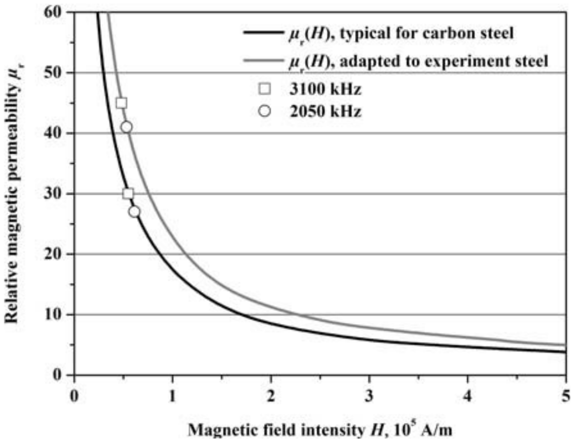

Fig. 9: $\mu_r(H)$- dependence at 20 °C

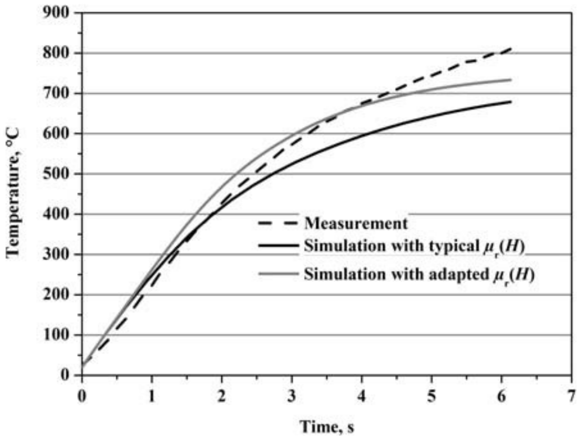

Fig. 10: Warm-up behaviour for 3100 kHz

New time-history temperature, simulated with the adapted $\mu_r(H)$-curve, is shown in Fig. 10. The correlation between the simulated warm-up behaviour after adaption of the $\mu_r(H)$-curve and the measured warm-up behaviour is much better than using the $\mu_r(H)$-curve for plain carbon steel.

Additionally, the adapted $\mu_r(H)$-curve has been checked at the lower frequency of 2050 Hz. The numerical result with the adapted $\mu_r(H)$-curve is also much closer to the experimental one than in case of the $\mu_r(H)$-curve for plain carbon steel (see Fig. 11).

With this method is it possible to find the correction coefficients for the actual location of the $\mu_r(H)$-curve for each particular steel. One big advantage of this method is that the determined values of relative magnetic permeability are already prepared to be used for numerical modelling of induction heating processes.

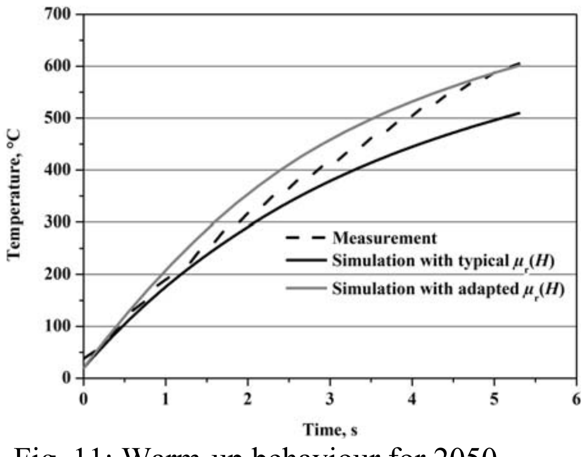

Fig. 11: Warm-up behaviour for 2050

2.5. Discussion and outlook

One can see that even new adapted values of magnetic permeability do not provide full correlation between the experimental and the numerical results. So there is potential to increase accuracy of the magnetic permeability identification. The next steps of investigation will be

- increasing the number of steel sheets of different thickness heated simultaneously (see Fig. 5). In this case, behaviour of two or more warm-up curves is compared for indirect μ_r-determination,

- increasing the number of parameters to describe the $\mu_r(H, T)$-dependence including the level of the Curie temperature, which can vary between 740÷780°C depending on current sort of steel.

3. Input data forms of relative magnetic permeability in numerical simulation of induction surface hardening

Full implementation of μ_r function (Fig. 1) to numerical models is very difficult, especially if the models are three-dimensional and/ or if the commercial program package in use does not support the double dependency of the input material properties. Only sensitivity analysis can show how exact the material properties must be implemented to the model in order to provide necessary accuracy of the simulated temperature distribution in the surface layer of the workpiece.

During the induction heating for surface hardening, the ferromagnetic workpiece passes through two heating phases in relation to its electromagnetic behaviour. In the first phase, named “cold phase”, the workpiece is completely ferromagnetic. The relative magnetic permeability is characterized all-over by the magnetization curve and temperature influence.

In the second phase, named “transitional phase”, the workpiece consist of two layers: a paramagnetic surface layer of a certain depth x_k with a temperature above the Curie point $T > T_c$ and a ferromagnetic core. This double layer behaviour is especially pronounced for very brief heating processes such as in induction surface hardening. The time period of the “cold phase” is much shorter than the time of the “transient phase”. The intensity of the magnetic field during the “transient phase” and its distribution toward the core of the workpiece play minor roles in forming the temperature field in the surface layer. This is because the surface material already becomes paramagnetic with $\mu_r = 1$ irrespective of H. It means that the qualitative distribution of temperature in the surface layer is not sensitive to the magnetic permeability behaviour in the ferromagnetic workpiece core.

3.1. The simulation models

Sensitivity analysis concerning the input data form of relative magnetic permeability has been carried out with two numerical models using identical two-dimensional geometry of computation area shown in Fig. 12. Model A allows automatically taking the dependence of μ_r from both parameters - temperature $T(x,t)$ und magnetic field $H(x,t)$ into account. In model B, the $\mu_r(H_0, T)$-function is implemented as a temperature dependent curve (Fig. 3) with a start value of μ_r at 20 °C taken from the curve in Fig. 9a. Therefore, model B only takes the μ_r-variation toward the core of the workpiece from the temperature into account. At the same time, the start value of μ_r at 20 °C is selected according to the value of magnetic field intensity H_0 on the surface of the workpiece.

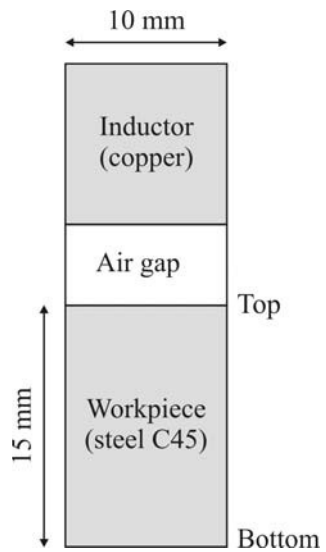

Fig. 12: Simulation model

The following topics are common for the investigation using both models A and B:

- the workpiece is to be seen as being placed inside a uniform axial magnetic field,
- a magnetic field of intensity H_0 is provided by an induction coil current which is applied to the model as an input parameter,
- temperature dependent material properties of steel are taken into account,

- simulation of short-time induction heating of 300 ms at frequency of 100 kHz,
- the hardened layer should reach the minimum austenitization temperature T_a of 850°C,
- maximum surface temperature of 1100°C at the end of heating.

3.2. Results

Three cases concerning the input data form of relative magnetic permeability have been simulated and compared. The model A was used for Case 1. The Cases 2 and 3 were simulated with model B. With Case 2, the start value of $\mu_r = 10$ at 20°C was defined in a manual iteration cycle. The Case 3 represents the situation if there is no information about the $\mu_r(H)$ for the tested steel. The start value of $\mu_r = 13$ at 20°C was the most probable estimated value.

Figs. 13-15 show the time dependent behaviour of temperature, μ_r - distribution at the heating end and temperature profiles at the heating end for all simulated cases. One can see that the time dependent behaviour of temperature differs depending on the input data form of relative magnetic permeability (Fig. 13). The μ_r-distribution and temperature distribution at the heating end (Figs. 14-15) are also different but only in the temperature range below the Curie point. In the temperature range important for induction surface hardening ($T > T_a > T_c$), the temperature profile at the heating end is identical for all three cases (Fig. 15). This fact allows us to assume that taking μ_r dependent on magnetic field intensity H toward the core of the workpiece into account, is not a necessary condition for a simulation of heating for induction surface hardening. The shape of the end temperature profile in the surface area is determined by the double layer medium only. Therefore, for the numerical computation it is enough to input μ_r as a temperature dependent curve with a start value of 20°C taken depending on H_0 ,as in model B. For actual steel sort, the $\mu_r(H)$-dependence can be determined by the identification method described above.

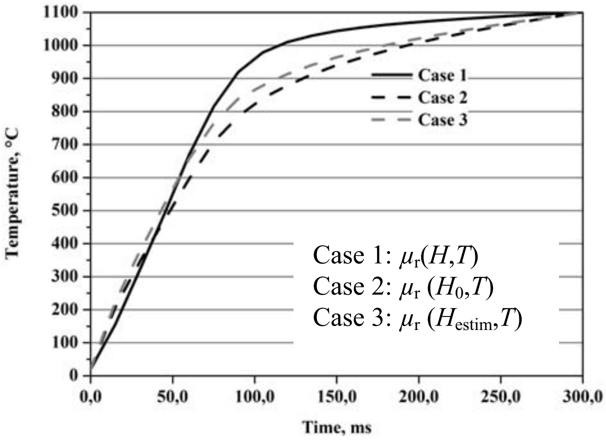

Fig. 13: Time dependent behaviour of temperature

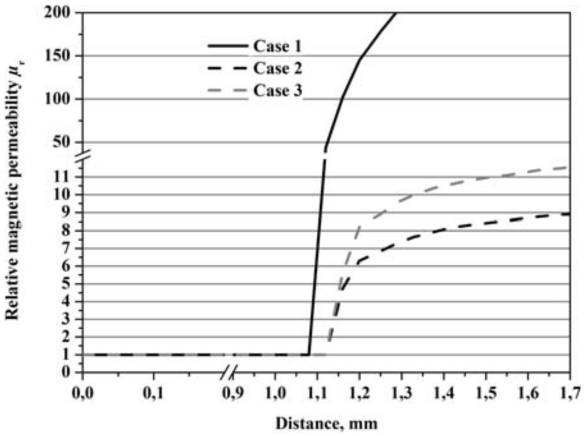

Fig. 14: μ_r - Distribution at the heating end

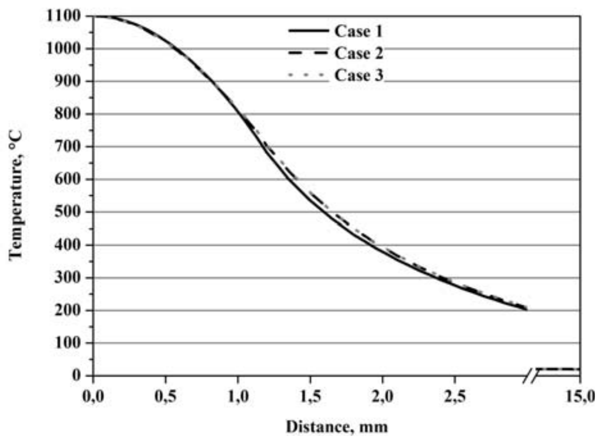

Fig. 15: Temperature profiles at the heating end

However, it should be considered that by making such an assumption, the input model parameters, quantitatively influencing the heating process (e.g. induction coil current), can slightly differ from the experimental values.

3.3. Experimental validation of the numerical predictions

To validate the numerically predicted temperature profile (model B) in the worm gear, the obtained hardened pattern experimentally has been used. The correlation between both profiles is very good (see Fig. 16). The simulated induction coil current values shown in Tab. 1 are very close to the experimental data as well.

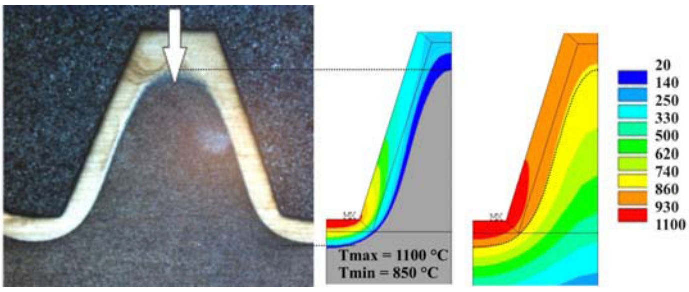

Fig. 16: Experiment vs. simulation, SDF-method, heating time 340 ms, F_{HF} = 260 kHz, F_{MF} = 12 kHz.

The comparison made confirms the assumption that for a numerical computation of temperature profile in the workpiece surface layer and therefore for predicting the future hardened profile, it is enough to input μ_r as a temperature dependent curve with a start value at 20°C taken depending on H_0. Moreover, investigations show that this assumption is also valid for numerical modelling of induction surface hardening made by the simultaneous double frequency (SDF) method.

Tab. 1. Experimental and numerical process parameters

Result	I_{HF}	I_{MF}
Experiment	3 kA	8 kA
Simulation	3,6 kA	9,6 kA

Conclusions

Investigations of relative magnetic permeability μ_r concerning numerical simulation of induction surface hardening have been carried out. A method of μ_r identification has been developed and successful tested. Sensitivity analysis of the input data form of relative magnetic permeability has been carried out. The adequate form for implementing to a model was found and verified experimentally.

References

[1] Sluhotsky, A., Ryskin, C.: *Induktory dlja indukcionnogo nagrewa (Inductors for the induction heating)*. Leningrad, "Energia", 1974.

[2] Rudnev, V., Cook, R., Loveless, D., Black, M.: *Steel Heat Treatment Handbook*, New York-Basel-Hong Kong, "Marcel Dekker, Inc", 1997

[3] Neuman, L.: *Poverhnostny effekt w ferromagnitnyh telah (Skineffekt in ferromagnetic materials)*. M.- L., "Gosenergoizdat", 1949, 190.

Authors

Dipl.-Ing. Zedler, Tatiana
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: zedler@ewh.uni-hannover.de

Dr.-Ing. Nikanorov, Alexander
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: nikanoro@ewh.uni-hannover.de

Prof. Dr.-Ing. Nacke, Bernard
Institute of Electrotechnology
Leibniz University of Hannover
Wilhelm-Busch-Str. 4
D-30167 Hannover, Germany
E-mail: nacke@ewh.uni-hannover.de