New nomographs for induction surface hardening of steel

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Abstract
New nomographs for induction surface hardening of steel showing the relations between surface power density, frequency, heating time, maximum surface temperature, and austenitisation depth have been calculated. Coupled electromagnetic and transient thermal 1D (ELTA) and 2D (Flux2D) simulations with nonlinear material properties have been used. A relative workpiece dimension factor is introduced to take into account the influence of the workpiece size.

Introduction

Induction surface hardening is a process controlled by several parameters and the final results are often approved after thorough testing of the part. Better tools for predicting the results do not eliminate the need for testing, but many of the premises for the final results are set when the test conditions are chosen. Good tools and a basic understanding of the process is therefore very important for both making the test phase effective and gaining an optimal result.

Nomographs can highlight relations between parameters influencing the process and serve as a supplementary tool in the test work.

In this paper, only results at 10 kHz are shown. The project has been a cooperation between Telemark University College, Politehnica University of Bucharest, EFD Induction GmbH, Freiburg, EFD Induction S.A., Grenoble and EFD Induction a.s, Skien.

Dimension factor

It is obvious that an accurate nomograph must consider the physical size of the part to be hardened. We have chosen to define a Dimension Factor as the ratio between workpiece diameter and temperature penetration depth. The temperature penetration depth, δ_{temp}, is considered to consist of two added elements:

1. Power penetration depth, δ_p, is equal to half the current penetration depth since power is proportional to the square of the current. We have used material properties corresponding to temperatures above Curie:

$$\delta_p = \frac{\delta_c}{2} = \frac{\sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}}}{2} = \frac{\sqrt{\frac{11{,}4 \cdot 10^{-7}}{\pi \cdot f \cdot 10^3 \cdot 4\pi \cdot 10^{-7}}}}{2} \cdot 10^3 \text{ mm} \approx \frac{8{,}5}{\sqrt{f\,[\text{kHz}]}} \text{ mm} \tag{1}$$

2. Thermal penetration depth, δ_{th}, for average values of the material properties in the temperature range from 700 to 1000˚C, is defined as:

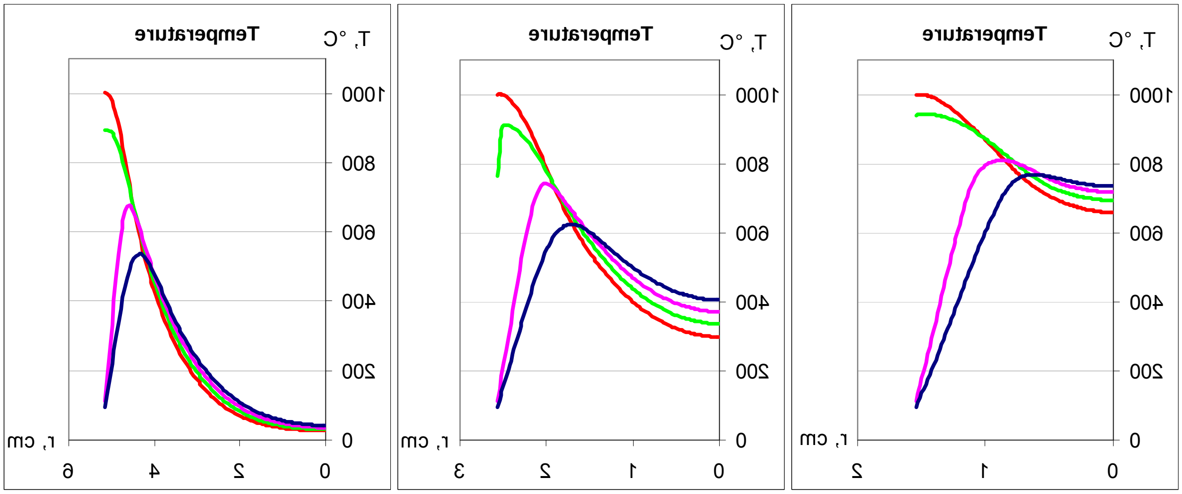
$$\delta_{th} = \sqrt{\frac{4 \cdot \lambda}{\pi \cdot c \cdot \gamma} \cdot t_h} = \sqrt{\frac{4 \cdot 28}{\pi \cdot 6.1 \cdot 10^6} t_h} \cdot 10^{-3} \text{ mm} \approx 2{,}4\sqrt{t_h\,[\text{s}]} \text{ mm} \tag{2}$$

The temperature penetration depth is then expressed:

$$\delta_{temp} = \delta_p + \delta_{th} = \frac{8{,}5}{\sqrt{f\,[\text{kHz}]}} + 2{,}4\sqrt{t_h\,[\text{s}]} \text{ mm} \tag{3}$$

In case of very short heating times, the temperature penetration depth will be more dependent on the material properties for temperatures below the Curie temperature. This definition should therefore not be used for heating times below 0,6s.

The dimension factor will express information about the temperature distribution within the part at the end of heating, as figure 1 show.



a) b) c)

Figure 1. Temperature as a function of distance from workpiece center, at the end of heating, and 1, 2 and 3 seconds after. d/δ_{temp} ratios: a): 10, b): 5 and c): 3

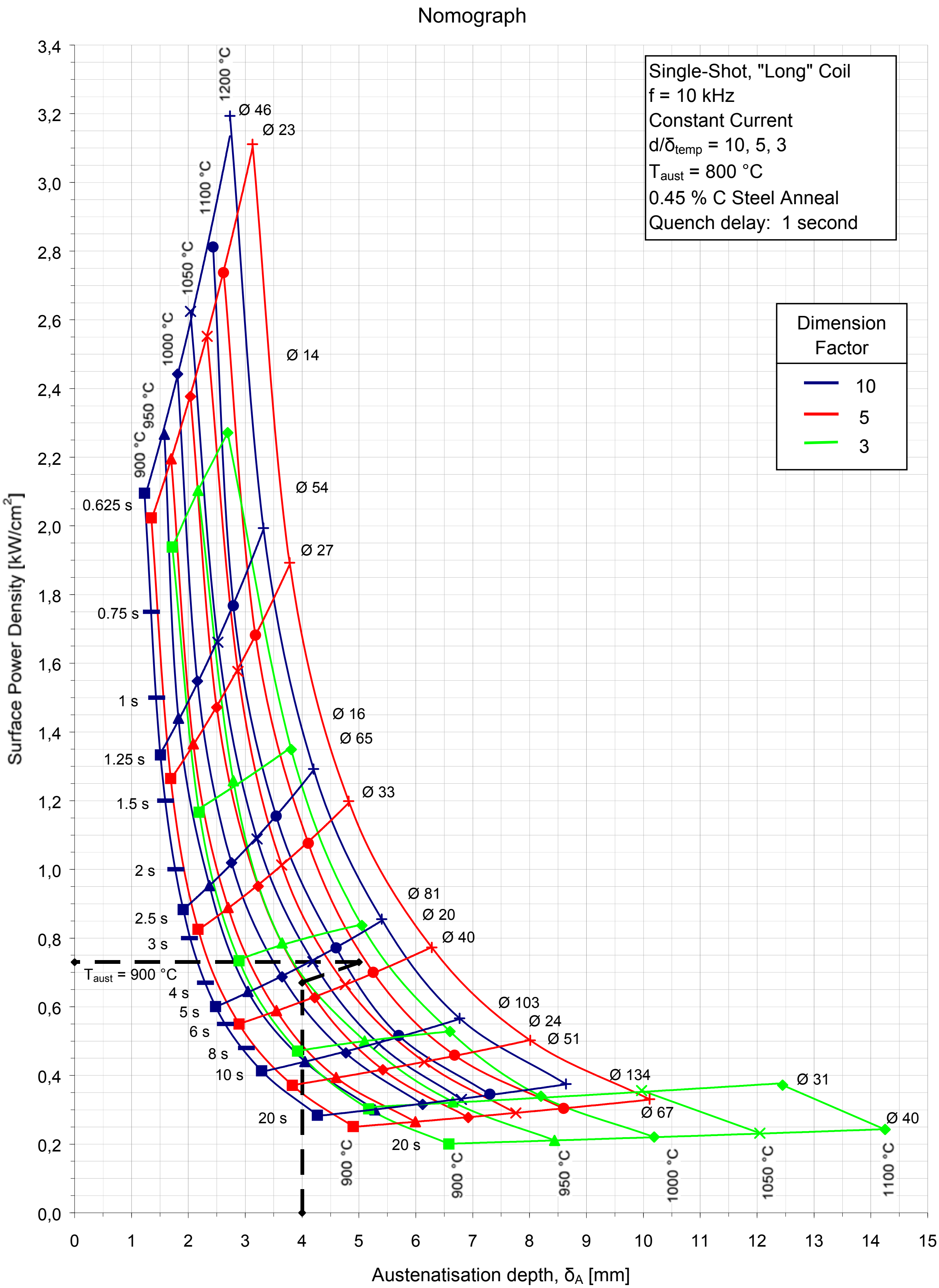


Figure 2. Nomograph for 10 kHz

Hardening depth

In order to select precise definitions, we have chosen to use austenitisation depth instead of hardening depth, since hardening depth depends on quenching conditions as well. In our calculations, we have applied a fixed quench delay of 1 second followed by cooling conditions corresponding to a normal spray quench. We have defined austenitisation depth as the depth to which the maximum temperature is equal to or higher than the set austenitisation temperature.

Classic nomograph, 10 kHz

The nomograph showed in fig. 2 is calculated with the 1D software ELTA based on the following conditions:

- The workpiece is cylindrical with a concentric coil. It is considered to be "long", that is, heat conduction is only in radial direction. This means that no end effects in axial direction are considered.
- Material properties for 0,45% Carbon steel annealed (unmodified from ELTA standard library) have been used.
- A constant sinusoidal current at 10 kHz is supplied to the coil for a time equal to the Heating time, t_h.
- Surface power density is average power density during the heating interval supplied to the workpiece.
- The time from power turn-off until the quenching starts is 1 second (quench delay).
- Temperature indicated on the curves is the maximum surface temperature at the end of the heating interval.
- Iso heating time curves are shown for the calculation points. The 900°C curve has a more detailed time scale with more points to make interpolation easier.
- The three different dimension factors 10, 5 and 3 are displayed in different colors. Some points for high temperatures and dimension factor 3 are missing because the conditions are very close to or causes through hardening.
- On the iso heating time curves, the corresponding workpiece diameter is indicated. It is thus possible to go directly into the curves without first assuming a heating time and calculate the dimension factor.

Practical hardening tests

We have checked the results against practical tests. Most of the test results were very close to the nomographs (0-10% deviation). A few measurements showed a deviation of up to 19%. When we take into account the measurement accuracy, we find the correspondence to be at an acceptable level.

Conclusions

The induction surface hardening process has many variables that have influence on the final result. The calculations done here are based on data for one typical steel quality, one defined austenitisation temperature and one selected quench delay. The nomographs are still intended to be a general-purpose tool. The user will therefore need to have a lot of skill in order to use the results correctly. Nomographs should bee looked upon as a supplement to practical tests. Used correctly they can help the user to better understand the process.