Computer simulation of steel microstructure composition for induction hardening of a splined shaft for various cooling rates

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***Abstract*— In this study, the microstructure in the hardened zone of a splined shaft after scanning induction heating with two-turn inductors is studied using computational modeling. Different steel microstructures such as bainite and martensite are shown to compare the relative hardness of the workpiece for different cooling rates. It is demonstrated that quick 2D axial-symmetric approximation could give reasonable estimations for gear hardening profile but the wider splines need 3D simulation for a good result. The influence of frequency and power is examined in the hardening profile of the splined shaft. All calculations were done by using CENOS simulation software, which uses a coupled electromagnetic-thermal model to describe the induction heating process. For microstructure calculations, a time-temperature transformation diagram was used.**

Keywords—splined shaft, induction heating, numerical modeling, surface hardening

I. INTRODUCTION

In the last decades, induction heating has become more and more popular because of the speed and energy efficiency for steel surface hardening and also other thermal treatment applications. The basic principle of induction heating is using an alternating current that creates a time-varying magnetic field which then induces eddy currents on the surface of the workpiece. Eddy currents heat up the workpiece due to the Joule effect. In the case of ferromagnetic material (as it often is in with steels) heating is happening also due to sudden jumps of the magnetic domain walls in the workpiece material called hysteresis losses. The depth in which eddy currents are induced depends on the frequency of the alternating current. Since heated is only the outside of the workpiece, it makes induction heating especially useful for surface hardening.[1]

Even though induction heating is sufficiently more energy effective than other hardening methods, often engineers face an obstacle on how to create the best design induction heating system. Since there are many parameters that have to be adjusted – frequency, heating time, power, current, and others, in more complex cases it is impossible to precisely analyze them. For this reason, in the last decades, numerical simulation procedure has become a tool for the successful design of complex induction heating and hardening systems. Numerical modeling can replace many expensive, time-consuming, and material wasting physical tests.

Until recently FEM software used to be a quite expensive tool that only enterprise level companies could afford. These tools also required highly qualified engineers with a good understanding of computational simulations to be able to run simulations in time and computationally effective ways. In this study, CENOS software was used to simulate induction hardening of the splined shaft. CENOS uses open-source tools, which have proven to give accurate and fast calculation results, and at the same time offering user friendly design for case building.[2]

In a previous study it has been shown that even though it is tempting to simplify this kind of axisymmetric geometry to 2D geometry, it will not give results accurate enough. Rather a 3D slice should be used as in fig 1. [3]

II. MICROSTRUCTURE CALCULATION

Induction hardening involves workpiece heating up to the austenitization temperature (Ac3) continued with rapid cooling (quenching). Different microstructures can be obtained in the steel piece by changing the speed of cooling. In CENOS cooling is done by changing the heat transfer coefficient of the workpiece surface. Knowing the distribution of steel phase microstructure at the end of the surface hardening is very important as it gives an understanding of the final stress in the workpiece.[1]

Martensite is the microstructure with the highest hardness which is normally wanted on the surface of the workpiece. If the cooling is relatively fast, a microstructure called martensite will be achieved, otherwise, other structures – ferrite, pearlite, and bainite starts to form (also called diffusional phases). To calculate austenite transformation to diffusional phases in CENOS software JMAK-type equation was used. [4] Since the finite element method is used, the

JAMAK equation is differentiated and the volumetric fraction of changed microstructure is calculated as:

$$\Delta f(t)_i = \left(k(T)n(T)t^{n(T)-1}e^{-k(T)t^{n(T)}}\right)\Delta t_i \tag{1}$$

Where constants k and n are:

$$n(T) = \frac{\ln\left[\frac{ln(1-f_s)}{ln(1-f_e)}\right]}{\ln(t_s/t_e)} \tag{2}$$

$$k(T) = -\frac{\ln(1-f_s)}{t_s^{n(T)}} \tag{3}$$

$f_s(T)$ and $f_e(T)$ are respectively points in Time-Temperature-Transformation diagram which represent the start and the end of transformation (respectively 1% and 99% fraction change) depending on temperature.

When the temperature falls under austenitization temperature (Ac3), phase change can occur. To define the beginning of phase change Scheil's additivity hypothesis was used.

$$\sum_i \frac{\Delta \mathrm{t}}{t_{1\%}} = 1 \tag{4}$$

The total fraction of the changed phase will be the summation of $\Delta f(t)_i$

$$f = \sum_i \Delta f(t)_i \tag{5}$$

III. RESULTS AND DISCUSSION

Engineers are often interested in the hardened profile of the workpiece, but in this study, we want to show, that hardened profiles do not give enough information if the hardening process needs to be fully understood. The temperature field in the workpiece is shown in fig. 2 which shows that reasonable temperature on the surface is achieved to perform surface hardening. In fig. 3a hardened profile, where temperature above austenitization temperature Ac3 was reached, is shown. In this case, moderate water flow was used as cooling with heat transfer coefficient from the surface 2000 W/m^{2}K. Now, when we look at the final microstructure distribution, we can see that the martensitic structure on the teeth surface is only 80%, but the base of the spline is only 20% martensite and 80% diffusional phases (ferrite, bainite, pearlite). Since the fully martensitic structure is wanted on the surface of the shaft, simulation can be used as a useful tool to pinpoint the flaws in the induction hardening process. In this case, we can see, that faster cooling is needed to achieve martensitic structure at the base of the teeth.

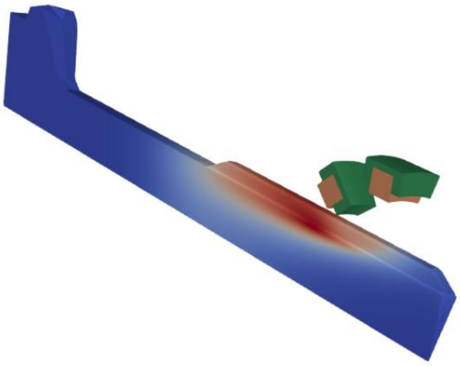

Fig 1: Illustration of the slice of full splined shaft geometry used for simulation.

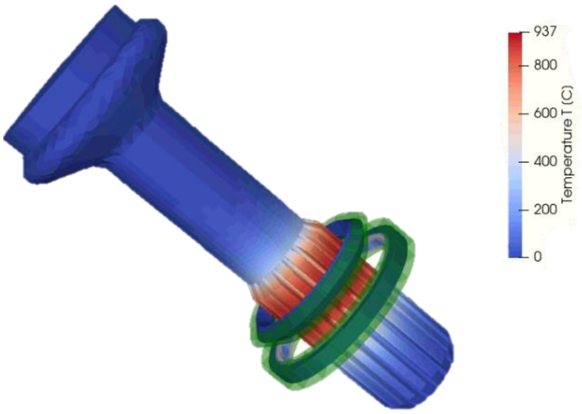

Fig2: Ilustration of full geometry with a sector view of inductors and flux concentrators

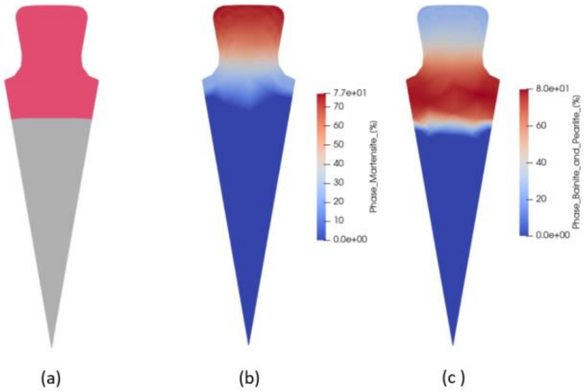

Fig 3: Splined shaft profile of the a) hardened zone b) martensitic structure field c) diffusional phase (ferrite, bainite, pearlite) field

REFERENCES

[1] ASM Handbook, Volume 4C: Induction Heating and Heat Treatment, ed. By Rudnev, V. & Totten, G. E., ASM International (Materials Park, OH, 2014).

[2] V. Geža, et al., "Potential of open source simulation tools for induction heating", IOP Conference Series: Materials Science and Engineering, , 424(1), 2018

[3] V. Geža, et al., "Simulation of scanning induction hardening for spline shaft", 30th ASM Heat Treating Society Conference and Exposition, Heat Treat 2019 - Extended Abstracts, , 1 43-47, 2019.

[4] J. Yuan and R. D. S. Jr, "FEM Modeling of Induction Hardening Processes in Steel," vol. 12, pp. 589–596, 2003