Induction Tempering of Surface Hardened Components

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Abstract—**Induction hardening is an energy-efficient and highly reproducible heat treatment process for surface hardening. Due to process-related thermal gradients between the surface and core areas of induction hardened components, the process is accompanied by residual stresses that promote crack formation. This problem is countered by tempering in the first tempering stage for a period of one to two hours after the hardening process. This is conventionally carried out in furnaces, which in the process chain involves additional transport and energy costs and prevents the production process from becoming more flexible. A resource-saving and environmentally friendly alternative is inductive tempering, which lasts a few seconds and enables integration into a running production line. The paper presents the results of a research project to develop a numerical model for the design of an induction tempering process, taking into account the previous induction hardening.**

Keywords—induction tempering, induction surface hardening, numerical simulation, FEM

I. Introduction

As part of the German AIF funding program, an innovative approach for modeling induction tempering in the process of inductive surface hardening was studied. The goal was twofold. On the one hand, the development of a comprehensive multi-physical numerical model of induction tempering that takes into account the previous induction hardening. On the other, the usage of the model for the field analysis in few inverse design test cases. The novelty of the paper mainly lies in the model of induction tempering since most of papers available in literature are limited to electromagnetic-thermal coupled analyses [1]-[2]. Our work not only considers hardening before tempering, but also it deals with three physics (electromagnetic, thermal, microstructural) in which all material properties (electromagnetic too [3]) are temperature and microstructure dependent.

II. Numerical Model

During the heating stages, in the integrated modeling of induction hardening and tempering processes, coupled electromagnetic-thermal and microstructural analyses have been considered. (Fig. 1). On the other hand, the quenching stages (occurring after both processes) are simulated in an analogous way, excluded the electromagnetic solution, here not necessary.

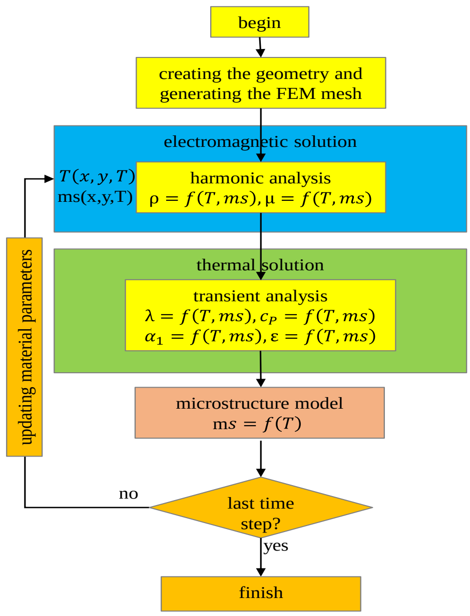
The electromagnetic analysis is described by the Maxwell equations evaluated in frequency domain. The magnetic permeability results to be not only temperature and field strength, but also microstructure dependent [3]. The electrical resistivity is temperature and microstructure dependent as well. Hysteretic losses are neglected because they play a very minor role compared to Joule' ones [4]. The thermal analysis relies on the heat conduction equation that includes convective and radiation effects. The source term depends not only on the induced power but also on the latent heat exchanged during phase-phase microstructural transformations. Finally, the microstructural analysis involves both heating and quenching stages in case of hardening. Therefore, it is able to predict the distribution of austenite and martensite. In case of tempering, the model evaluates the map of carbides and, mostly important, the final hardness. This is obtained as a rule of mixture from the different microstructures. In particular, the hardness of tempered martensite is calculated as a linear dependency from the Hollomon-Jaffe tempering parameter (*TP*):

$$TP = \frac{T + 273.15}{1000}\left(C + \log\frac{t}{3600}\right)$$

Where *T*, *t*, *C* are temperature, time and a material constant, respectively. It is straightforward to recognize that, compared to the conventional treatment, induction tempering, due to the short heating time, requires higher temperatures to get an equivalent hardness reduction. However, the temperature increase is much more limited in comparison to the time diminution.

Simulations were carried out with the commercial software package ANSYS® making extensive use of user-written subroutines to guarantee enough flexibility in the modelling step. The work-piece is always supposed to be made of AISI 4140 (German grade 42CrMo4).

Fig. 1. Electromagnetic-thermally coupled model with feedback of the temperature and microstructure dependent electro-magnetic and thermo-physical material data

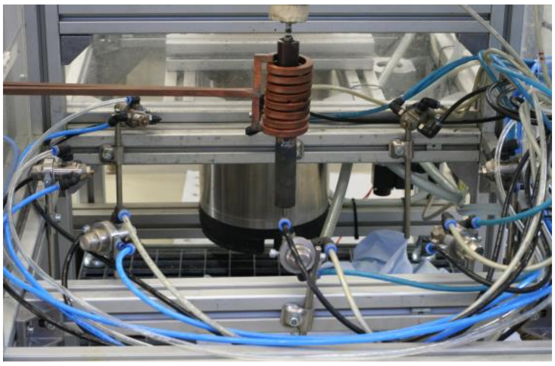


III. PROJECT RESULTS

A. *Verification of the numerical model with a test configuration*

A test-setup has been built in our laboratory in order to validate the numerical model (Fig. 2). The choice of a cylindrical work-piece comes from the will to minimize the sources of inaccuracy. The heating processes, in both hardening and tempering, are performed with the same inductor. Moreover, as in most industrial applications, in order to facilitate the integration in the production line, tempering and hardening employ an equal frequency. With a desired hardening depth of 2 mm, the choice falls on 12 kHz [5]. In the hardening process, in order to guarantee the transformation of austenite in martensite, heating must be followed by the quenching. In our test-setup pressurized water is used as quenching medium. Validation includes comparison of simulated and measured temperatures.

Fig. 2. Test-setup at ETP. The 8-windings coil is surrounded by 8 nozzles that are responsible for the cooling



B. *Verfication of hardening and tempering models of the industrial process*

Preliminary experiments in industry have been performed. The work-piece under analysis has a “L-shape” and the inductor consists of a single turn surrounded by flux concentrating material (Fig. 3). Such piece geometries are broadly diffused in automotive and aerospace components. During the heating processes, the surface temperature is measured with a pyrometer through a hole in the coil. The heating time in the hardening process has been chosen equal to 0.5 s. The power supply provides a constant power of 100 kW while the frequency is 12 kHz. A good agreement has been reached between measured and simulated temperature (Fig. 4).

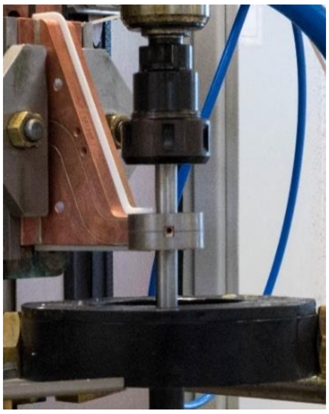
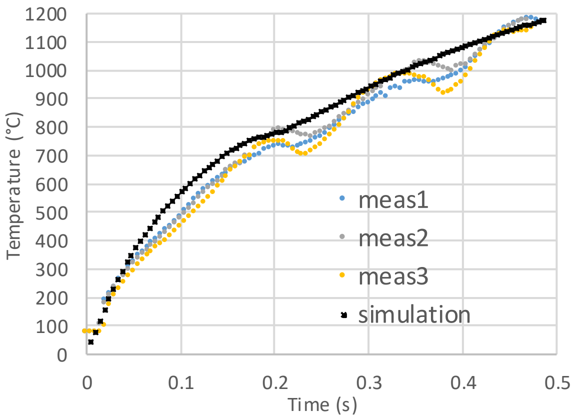


Fig. 3. Experimental setup in industry

Since the whole tempering process occurs under the Curie temperature and the used frequency remains 12 kHz, in order to avoid overheating, it is mandatory to modulate the power in time. In this case, three 8 kW power pulses are followed by as many soaking intervals. The total time is just below 20 s. Similar to hardening, also in tempering the simulated temperature meets excellently the experimental results. Final hardness distributions show good agreement too.

Fig. 4. Hardening: comparison between simulated (black) and measured temperatures (meas1, meas2, meas3)



C. *Inverse design of an industrial induction hardening and tempering configuration*

Once the numerical model has been validated, it has been used for the inverse design of the overall heat treatment. Ideally, given the wished final hardness distribution, our numerical tool is capable to predict the inductor geometry and the heating regimes (power, time and frequency in both hardening and tempering). Few inverse design test cases relative to induction tempering have been performed. Design variables concerned the heating profiles, while the objectives relate to a uniform hardness distribution around a desired value and/or a short time process. If in the preliminary experiments, the maximum deviation from 58 HRC varied between 3.3 and 5.5 HRC, thanks to the inverse design this value dropped to 2.1 HRC. A further reduction was achieved exploiting the residual heat during quenching after hardening.

SUMMARY

A multi-physical numerical tool has been developed for the simulation of induction hardening and tempering in order to get a better understating of the overall process and exploit the advantages of the induction technology: time and energy saving among all. Results of the inverse problems look encouraging in the hope of making this technology attractive.

ACKNOWLEDGMENT

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