Design of induction tempering of surface hardened components

Marco Baldan, Bernard Nacke
Institute of Electrotechnology, Leibniz University Hannover, Wilhelm-Busch-Strasse 4, 30167, Hannover, Germany
E-mail: baldan@etp.uni-hannover.de

Abstract. Induction hardening is a well-known heat treatment in the automotive and aerospace industries. Very often it is accompanied by tempering that is conventionally performed in ovens. However, induction tempering is getting more popular and this introduces the chance of using numerical simulations and optimization in the design stage. In this paper, based on a real case study, we will describe how to model and choose the regime parameters in both induction hardening and tempering.

1. Introduction
Mechanical parts, such as shafts, pinions, gears, and hubs, are ever-present components in automotive and aerospace. They are subjected to surface treatments in order to improve their ware behaviour and vibration resistance. Induction hardening determines a hard surface layer with compressive stresses, which has proved to be effective in augmenting the piece's fatigue life and wear resistance [1]. After hardening, the components are often tempered to diminish the chance of crack formation and to enhance toughness and ductility. The interest in induction tempering has grown in the last years, since in comparison to the conventional treatment (i.e. in oven), the process time is significantly reduced (seconds instead of hours) [2-6]. Moreover, induction tempering is easily embeddable in the production line.

In 2019, almost 92M (i.e. 92 millions) vehicles were produced worldwide and this trend is growing. The world of automotive is experiencing a significant change that will strongly affect the entire sector of induction heating (machine producers, hardening shops...) too. It is mostly probable that the amount of inductively treated pieces will be heading for a contraction in the nearest future. But nonetheless, the induction technology will be pushed to achieve better standards and quality. Using numerical modelling can definitely help in this sense. Multi-physical numerical modelling of induction hardening has a long story that started in 90s [7-8]. The interest in simulating tempering is much more recent. Several works regarding multi-physical modelling of the conventional treatment do exist [9-12]. When one refers instead to induction tempering, models are typically limited [4], [6].

In this paper, a multi-physical numerical model of both hardening and tempering was adopted. The model includes the electromagnetic, thermal, and metallurgical analyses. This is already a novelty. Moreover, our work focuses on the design of the processes too. So far, the use of multi-physical models in induction tempering has not been extensively investigated. The paper is developed as follows. Firstly, a quick description of the numerical model is given. In a separate work we will describe the model more in detail. Then, different strategies regarding how to design the regimes in the induction hardening-tempering process are investigated.
2. Multi-physical numerical model

The multi-physical numerical model of induction hardening-tempering includes three different physical analyses. The electromagnetic analysis is described by the Maxwell equations evaluated in frequency domain [14]:

\[
\nabla \times (\mu_r \mu_0)^{-1} \nabla \times A + j \omega (\mu_r \mu_0) \rho^{-1} A = -\rho^{-1} \nabla V, \quad (1)
\]

\[
\nabla \cdot \rho^{-1} (j \omega \mu_r \mu_0 A + \nabla V) = 0, \quad (2)
\]

where A stands for the magnetic vector potential, V represents the electric scalar potential, \( j = (-1)^{0.5} \), and \( \omega \) is the angular frequency. The magnetic permeability (\( \mu \)) results to be not only temperature and field strength, but also microstructure dependent [13]. The electrical resistivity (\( \rho \)) is temperature and microstructure dependent as well. The thermal analysis relies on the heat conduction equation:

\[
\nabla \cdot (\lambda \nabla T) + \rho_t c_p \frac{\partial T}{\partial t} = \dot{q} \quad (3)
\]

In which T denotes the temperature, \( \lambda \) indicates the thermal conductivity, \( \rho_t \) and \( c_p \) the density and the specific heat, respectively. \( \dot{q} \) describes the heat source density.

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 the final hardness (\( H \)). 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 [15]:

\[
TP = \frac{T+273.15}{1000} \left( C + \log \frac{t}{3600} \right) \quad (4)
\]

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.

3. Optimal design of the hardening process

Designing a hardening process involves mainly two aspects. On the one hand, the definition of the optimal regime. This includes the heating time, the frequency and the power (or inductor current, or voltage). On the other hand, there is the inductor geometry. One possible way to find the optimal parameters (i.e. current, frequency, time, shape and dimensions of the inductor) is to build a numerical model, formulate an objective function, which is dependent on all these parameters, and couple the model with some optimization algorithm. However, a smarter approach does exist [16]. Indeed, the regime parameters can mostly influence the hardness (i.e. martensite) distribution in the depth. On the contrary, the inductor geometry influences the contour of the hardness profile. To a first approximation, since the desired hardening depth (\( hd \)) is known when designing a hardening process, the regime parameters can be adjusted in such a way that the wished hardening depth is achieved. In order to do that, a 1D model could be employed to define the optimal time and frequency, without resorting to using the numerical model with the real geometry. From this analysis, an estimation of the needed density power is also obtainable. Once time and frequency have been set, the process design can be focused only on the inductor geometry. The power (or inductor current or voltage) needs only to be adjusted. Therefore, one can think about optimizing the inductor through an optimization problem in which only geometrical variables appear (in addition to the adjustment of power or current).
In the 1D model one can recognize three parts: the inductor (a massive piece of copper), the air gap, and the piece (made of steel). The task is to find the optimal regime, given the desired hardness depth. For simplicity, it is assumed that the austenite and martensite distributions coincide. This is reasonable for thin (few mm) hardness depths and relevant quenching intensities. Moreover, the full austenitization model will be not used. The aim is that the whole hardness depth overcomes the $A_{C3}$ temperature. It is interesting to study the trade-off between the surface temperature and energy consumption. This is formulated as:

$$\min_{I, f, t_h} F(I, f, t_h) \ with \ I = \arg \min \ g(i, t, t_h) \ \ (5)$$

in which $I$ is the current (assumed constant during the heating), $f$ is frequency, and $t_h$ is the heating time. The objective functions are $f_1 = T(t_h, 0)$ (the surface temperature at the end of heating), $f_2 = \int P \ dt$ (the energy consumption), and $g = |T(t_h, hd) - A_{C3}|$, which represents the deviation from $A_{C3}$ of the final temperature at the border of the hardening depth. In this case, the frequency range is [5-30] kHz, while the heating time changes between 1 and 5 s. Once (5) has been solved, it turns out that the “image” of the non-dominated solutions shows that, surprisingly, the front can be divided into two parts. In the “left” part, all the points assume the minimum range frequency, whereas in the “right” one, the heating time is always at minimum. From these results one can conclude that the frequency plays a minor role compared to the heating time in terms of energy consumption. In other words, in this approach, the choice of the variable ranges directly affects the obtained Pareto front. Therefore, a new strategy was adopted. In the Pareto front, the point with the lowest energy consumption is the point with the optimal frequency and minimum time. This means that a multi-objective optimization approach is here overabundant. Considering a typical heating time, the optimal frequency could be evaluated considering the energy consumption ($f_2$) as a unique objective function. With a heating time of 1 s, the minimum is located between 19 and 20 kHz (Fig. 1). The curve is a bit noisy because the value of $g$ is not always zero and it differs for each individual.

![Figure 1](image1.png)  
**Figure 1**: Energy consumption as a function of frequency ($t_h=1$ s, $hd=2$ mm) (a); trade-off between surface temperature and energy consumption with $f = 19.5$ kHz. Labels indicate the heating time (b).

In case of a 2.2 mm hardening depth, with a heating time of 0.5 s, the optimal frequency is 15.2 kHz (theoretical value is 12.4 kHz [17]). This motivates the choice of working with a frequency in between in the real application (Fig. 2). The geometry of the one-turn inductor is assumed given, the component is a L-profile made of AISI 4140. The hardness level after hardening is approximately 62 HRC.
Figure 2: Sketch of the real application. A one-turn inductor with magnetic flux concentrator is used.

4. Optimal design of the tempering process
In this section the tempering regime is optimized, in order to smooth the hardness distribution around a value within the hardness depth. The inductor geometry will not change (Fig. 2). It means that the hardness in the axial direction is only slightly affected. The task is an optimal control problem. Inspired by the "alternance method" approach [18], the study starts with only one pulse followed by the soaking time (2 variables) and up to three pulses will be considered. $t_a$ denotes the time in which the power supply is on, $t_s$ when it is off. After the last soaking stage, the piece is quenched down. The inverse problem is defined as the maximum deviation from 58 HRC within the hardening depth:

$$\arg\min_{t_{a1}, t_{s1}} \max |H - 58|$$

(6)

Therefore, we would like to reduce of 4 HRC the hardness level, which, in case of induction tempering, represents a challenging task. The power is the minimum achievable in the real application and it is equal to 8 kW. No constraints relative to the tempering stage or to the values of $TP$ are implemented. Tab. 1 indicates the obtained values of the optimal variables. As expectable, increasing the number of pulses allows to flatten more and more the hardness distribution around 58 HRC. Tab. 1 also recalls the hardness difference within the hardness depth. Notice that the maximum deviation from 58 HRC is approximately the half of the hardness difference $\Delta H$. This is a good sign. Alternance method makes use of this property to define in advance how the optimal solution is supposed to look like. Fig. 3 shows the three optimal hardness distributions. Only in case of three pulses a successful final hardness profile is obtained.

Table 1. Results of the three inverse problems relative to the heating regime and hardness distribution.

| Inverse Problem | Pulses | $t_{a1}$ | $t_{s1}$ | $t_{a2}$ | $t_{s2}$ | $t_{a3}$ | $t_{s3}$ | $\Delta H$ | $\max |H - 58|$ |
|-----------------|--------|----------|----------|----------|----------|----------|----------|-----------|-------------|
| 1               | 1      | 1.69     | 4.64     | -        | -        | -        | -        | 6.40      | 3.21        |
| 2               | 2      | 1.41     | 1.24     | 0.60     | 1.91     | -        | -        | 4.94      | 2.47        |
| 3               | 3      | 1.27     | 3.65     | 0.68     | 1.67     | 0.47     | 2.40     | 4.13      | 2.09        |
Figure 3. Optimized hardness distribution in the three inverse problems.

From the previous analysis one can conclude that induction tempering is particularly suitable for small hardness reductions. In case the desired hardness is 58 HRC, the reached maximum deviation was never below 2.09 HRC. In general, in industrial applications, a tolerance of ±2 HRC is the standard. Now, still referring to the same setup (piece, inductor, frequency), the aim is trying to further smooth the hardness distribution after tempering around 58 HRC. So far, the quenching process after hardening was 15 s long and it allowed to cool the piece up to room temperature. However, the formation of martensite is almost completed around 200 °C (at least in case of AISI 4140). By shortening the quenching time ($t_Q$), it is possible to use the heat still present in the piece (especially close to the core) to get a tempering effect on the martensitic surface (self-tempering).

It is now investigated whether combining self- with induction tempering could be beneficial in order to get a final homogeneous hardness of 58 HRC. It is still assumed that tempering is performed right after hardening with same power supply, and therefore the minimum power available is 8 kW. Two cases are considered: in the first one, the quenching time is 3 s, in the second is 2.5 s. Afterwards, two inverse problems are run (IP4, IP5), aiming at smoothing the hardness curve around 58 HRC. Heating regimes are defined by two pulses. Hardness results are depicted in Tab. 2. Having a quenching time of 3 s does not seem to be so helpful. With a successive two pulses tempering, the maximum deviation from 58 HRC is 1.91 HRC (it was 2.47 HRC in the case without self-tempering). On the contrary, when the quenching time is 2.5 s, again with a subsequent two steps tempering, the max-norm falls to 1.22 HRC. This leads to a significant hardness flattening.

| Inverse Problem | Pulses | $t_Q$ (s) | $t_{a1}$ (s) | $t_{s1}$ (s) | $t_{a2}$ (s) | $t_{s2}$ (s) | $\Delta H$ | $\max |H - 58|$ |
|----------------|--------|-----------|-------------|-------------|-------------|-------------|-----------|-------------|
| 4              | 2      | 2.5       | 1.42        | 3.10        | 0.61        | 2.71        | 3.77      | 1.91        |
| 5              | 2      | 3         | 1.32        | 2.31        | 0.51        | 3.71        | 2.40      | 1.22        |

Table 2. Hardness distribution after self-tempering and optimized induction tempering (8 kW).

5. Conclusions

In this paper it has been introduced a multi-physical model of both induction hardening and tempering. However, the main focus has been on the design of the processes. Firstly, it has been described how to choose the optimal heating time and frequency in hardening. Then, it has been investigated how to flatten the hardness profile around 58 HRC using tempering. Combining self- and induction tempering resulted to be a winning strategy, since the obtained maximum deviation was only 1.2 HRC.
6. References

[1] Rudnev V, Loveless D, Cook D and Black M 2003 Handbook of induction heating Marcel Dekker Inc.

[2] Euser V, Williamson D, Clarke K D, Findley K O, Speer J G and Clarke A J 2019 Effects of Short-Time Tempering on Impact Toughness, Strength, and Phase Evolution of 4340 Steel Within the Tempered Martensite Embrittlement Regime Metallurgical and materials Transactions A 50(A) pp. 3655-3662.

[3] Kaiser D, De Graaff B, Dietrich S and Schulze V 2017 Investigation of the tempering process of martensitic AISI 4140 steel at high heating rates Proc. of IFHTSE Congress 2017.

[4] Zabett A and Azghandi S 2012 Simulation of induction tempering process of carbon steel using finite element method Materials and Design 36 pp. 415-420.

[5] Sackl S, Zuber M, Clemens H and Primig S 2016 Induction Tempering vs Conventional Tempering of a Heat-Treatable Steel Metallurgical and Mat. Tra. A 47A pp. 3694-3702.

[6] Vieweg A, Raninger P, Prevedel P, Ressel G, Ecker W, Marsoner S and Ebner R 2017 Experimentelle und numerische Untersuchung des induktiven Anlassens eines Vergütungsstahles HTM J. Heat Treamt. Mat 4 pp. 199-204.

[7] Bokota A and Iskierka S 1998 Numerical analysis of transformations and residual stresses in steel cone-shaped elements hardened by induction and flame methods Int. J. Mech. Sci 40(6) pp. 617-629.

[8] Simsir C 2014 Modeling and Simulation of Steel Heat Treatment-Prediction of Microstructure, Distortion, Residual Stresses, and Cracking ASM Handbook 4B pp. 409-466.

[9] Deng X and Ju D 2013 Modeling and Simulation of Quenching and Tempering Process in Steels Physics Procedia 50 pp. 368-374.

[10] Eser A, Broeckmann C and Simsir C 2016 Multiscale modeling of tempering of AISI H13 hot-work tool steel – Part 2: Coupling predicted mechanical properties with FEM simulations Computational Materials Science 113 pp. 292-300.

[11] Tong D, Gu J and Yang F 2018 Numerical simulation on induction heat treatment process of a shaft part: Involving induction hardening and tempering J. of Materials Proces. Tech. 262.

[12] Baldan M, Nikanorov A and Nacke B 2020 A parallel multi-fidelity optimization approach in induction hardening COMPEL - The international journal for computation and mathematics in electrical and electronic engineering 39(1) pp. 133-143.

[13] Baldan M, Stolte M H, Nacke B and Nuernberger F 2020 Improving the Accuracy of FE Simulations of Induction Tempering Toward a Microstructure-Dependent Electromagnetic Model IEEE Transactions on Magnetics 56(10).

[14] Schlesselelnmann D 2016 Methoden zur numerischen Berechung, Analyse und Auslegung induktiver Randschichthärteprozesse unter Berücksichtigung von magnetischen Sättigungseffekten PZH Verlag.

[15] Hollomon J and Jaffe L 1945 Time-temperature relations in tempering steel Trans. AIME 162:223.

[16] Baldan M, Nikanorov A and Nacke B 2018 Hierarchical optimization approaches in designing surface hardening induction systems IOP Conf. Ser.: Mater. Sci. Eng. 424 012067.

[17] Sluhotsky A and Ryskin C 1974 Inductors for the induction heating Energia.

[18] Rapoport E and Pleshivtseva Y 2006 Optimal control of induction heating processes T&F.

Acknowledgments

Authors would like to acknowledge the program for the promotion of cooperative industrial research (IGF No. 20008 N) via the German Federation of Industrial Research Associations (AiF) e. V. on the basis of a resolution of the German Bundestag.